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Fidelity of Simulation for Pilot Training

NORTH ATLANTIC TREATY ORGANIZATION

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PREFACE

The training flight simulator is a device for the acquisition, development, and maintenance of flying skills. Its use may give considerable savings in flying time, flying space, fuel consumption, and aircraft life and also enable trainees to carry out operations which in the actual aircraft would be dangerous to life and machine. These advantages have been recognized, and flight simulation is now widely established as a method for pilot training.

Unfortunately, simulators are tending to become as complex and expensive to acquire as the aircraft for which they are surrogate. Serious questions have been raised, in both the technical and training communities, as to the complexity of simulation that is required for effective pilot training. Accordingly, AGARD established Working Group 10 in March 1978 and defined its primary objectives as follows:

1. To review the scope and effectiveness of current flight training in simulators

2. To review the status of technologies and human behavior important to the fidelity of flight simulation

3. To identify research objectives in the areas of simulation technologies and training that might lead to increased cost-effectiveness in simulator training

The Working Group evolved from a recognition by the AGARD Aerospace Medical Panel (AMP) and the Flight Mechanics Panel (FMP) that a multidisciplinary approach was required in assessing simulation for training. The FMP has capability to advise on the technical and engineering problems associated with fidelity of flight simulation, but is not a suitable group to deal with psychological and physiological problems on the subject. As a result, AGARD decided on a combined effort between AMP and FMP, with AMP being the lead panel. The intention was that engineers, psychologists, and physiologists should operate as a team, rather than independent contributors, in order to obtain optimal efficiency in future simulator designs.

The Working Group formed three subgroups, each studying a main theme:

SG1 Relevant engineering aspects of flight simulation hardware

SG2 Training objectives

SG3 The nature of cues experienced and used by a pilot when flying an aircraft, and the translation of these cues into simulator hardware

The Working Group structure provided excellent and valuable cross-fertilization of ideas. Each of the three subgroups identified a broad range of topics covered by the notion of "simulator fidelity for pilot training," and when these topics were considered together, the Working Group found itself with a problem of very large dimensions. The main achievement of this report is the articulation of these broad concerns and the definition of more specific questions that must be addressed in further detail.

The members wish to acknowledge the valuable contributions of Dipl. Ing. Schulz-Helbach who passed away in November 1979 and dedicate this report to his memory.

Special acknowledgment is made to Dr. Wayne Waag of USAF Human Resources Laboratory for his extensive contributions to the section on Pilot Training.

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FIDELITY OF SIMULATION FOR PILOT TRAINING

1. INTRODUCTION

The purpose of this report is to focus attention on the subject of fidelity requirements for training simulators and to provide background for the multidisciplined community involved in developing these devices. Weaknesses in current methods of specifying training devices have been identified, and a different approach is proposed. Gaps in the required technology have also been identified, and appropriate research topics are suggested. It is hoped that, by establishing a dialog between the training community and the simulator technologists, these recommendations will eventually lead to more cost effective devices.

1.1 Background

The coming of age of flight simulators was celebrated in 1979 by the joint Royal Aeronautical Society/ American Institute of Aeronautics and Astronautics Conference: "Fifty Years of Flight Simulation." Several papers reviewed the history of simulator development, and it seems appropriate to quote Skans and Barnes (Ref. 1):

> "The success of flight simulation applied to airline training is reflected in the widespread use which is today made of simulators. Eighty airlines all over the world operate simulators to a total value of more than one billion dollars. Forecasts are of an expanding market. Simulators for more than eighty types of passenger carrying aircraft have been built. Many more procedures trainers have seen service.
>
> If the use of simulators in the civil field is expanding, then the use of simulators in the military field is exploding. Much of the same reasons — fuel savings, better training environment, cost and time saving — explain the expansion. Additional factors make the use of military simulators even more attractive. The saving of airframe fatigue life is one example; another is the reduced need to train over countryside where environmentalists are nesting. One other distinction can be made between military and civil use of simulators. Because much of the time of a military pilot is spent in training, simulators can be used to reduce the number of aircraft needed by an air force over a period of time. The same benefit is not available when the task is to carry passengers.
>
> Perhaps the best reason of all for the increasing use is that military training simulators are now appearing which can deal with most of the specialized aspects of pilot training — flight refueling, air-to-air combat, air-to-ground attack and operations close to the ground."

Herein lies the genesis of the topic for this Working Group and this report: Just what fidelity is required to train? Is a motion system required? Is a visual system required? If they are required, what characteristics should they have? Answers to such questions can have significant impact on the cost and complexity of training facilities, and better information for making such judgments is sorely needed. It is worthwhile emphasizing at this point that the study is focused on fidelity of simulators for pilot *training*. It does not consider simulation for research and development to support studies involving the pilot aircraft interface with the intent of getting better aircraft. Significantly different fidelity requirements may exist for the latter application.

Before developing arguments any further, it is worthwhile to look at just what is meant by "fidelity of flight simulation."

1.2 Simulator Fidelity

Much has been written on what is meant by fidelity of simulation for training. Just defining the term seems sufficiently confusing without adding the question, to be addressed in this report, of how much fidelity is required to train. The following definitions, inspired by a USAF HRL statement of work addressing the topic of fidelity testing for training simulators, seem to come to grips with the facets of fidelity that are within the scope of this study and will be used as consistently as possible throughout the rest of this report.

First it is convenient to divide the constituents of a simulator into two classes depending on the nature of the cues they provide: *Equipment cues* provide a duplication of the appearance and feel of the operational equipment (the aircraft), i.e., the static and internal dynamic characteristics such as the size, shape, location, and color of controls and displays, including controller force and displacement characteristics. *Environment cues* provide a duplication of the environment and motion through the environment. The most obvious examples are motion from platforms or "g" seats and visual out-of-the-window cues.

The degree to which these equipment and environmental cues match those of the aircraft is generally what is understood to be fidelity. However, a subtle distinction has to be made here between the real cues measured objectively and the cues the pilot subjectively experiences. Thus, we have the following definitions for two types of fidelity:

a. *Objective fidelity* provides an engineering viewpoint and is the degree to which a simulator would be observed to reproduce its real-life counterpart aircraft, in flight, if its form, substance, and behavior were sensed and recorded by a nonphysiological instrumentation system onboard the simulator. By including both equipment and environmental cues, this definition can encompass all pertinent dynamic cue timing and synchronization aspects of simulator fidelity.

b. *Perceptual fidelity* provides a psychological/physiological viewpoint and is the degree to which the trainee subjectively perceives the simulator to reproduce its real-life counterpart aircraft, in flight, in the operational task situation. The requirement that the operational equipment be considered in the context of the task situation ensures that not only cue timing and synchronization, but also cue priority effects, are taken into account.

Thus, the Working Group's objective could be interpreted as to define for each source of cues, equipment and environment, how much perceptual fidelity is required to achieve satisfactory training, and then, how much objective fidelity is required to achieve the desired level of perceptual fidelity.

One cannot assume that high fidelity necessarily results in better training. Therefore, since a primary motivation is to minimize costs of training, the primary focus of this study should be the high cost areas. The hardware components that have maximum cost and technology impact are probably:

- Visual display characteristics such as field of view, resolution, detail, dynamic response, etc.
- Motion system characteristics such as scaling of cues, smoothness, bandwidth of response matching, and extent of miscuing.
- Math model, i.e., the mathematical representation of the simulated aircraft.

High fidelity in any or all of these characteristics is achieved at significantly higher cost than low fidelity. Motivation for this study is to obtain background information on the effect of simulator fidelity on training capability so that agencies can make informed choices on cost versus training when they procure or regulate characteristics of new systems. In addition to cost, many factors, such as the type of training (e.g., ab initio, proficiency, or conversion training), aircraft type, and mission flight phases that have to be trained, will impact on the facility requirements. It is fairly obvious that the facility required to train a helicopter pilot to do certain tasks in nap-of-the-Earth (NOE) flight are different from those required to train a fixed-wing aircraft pilot in IFR terminal area flight. It is less obvious, but true, that a simulator required to teach a new inexperienced pilot IFR terminal area flight will be different from one required for an experienced pilot to maintain proficiency in the same tasks or to transition from one aircraft type to another. This is not to say that the ab initio pilot could not be taught in the same simulator as the experienced pilot, but rather that a cheaper and simpler facility could probably do just as effective a job. Two other factors will influence the choice of simulator facilities: the size of training throughput and the aircraft fleet mix. If there is a large pilot throughput, it may be cost effective to develop several part-task trainers (PTT) as well as a full-mission simulator (FMS). This would allow less expensive PTT devices to be used to supplement time on the expensive FMS. Conversely, if a small number of pilots are to be trained, the usefulness of the PTT may soon be exhausted, and their low utilization may easily be accommodated on the FMS. The impact of aircraft fleet mix can arise because there may be a particular flight phase common to several aircraft (e.g., the USAF requires air combat maneuvering (ACM) to be taught for the F-4, the F-5, A-7, and F-15). In this case, rather than including ACM in an FMS for each type, the PTT could be developed just for ACM with the basic characteristics of each or all of the subject airplanes.

Such considerations as those outlined above, or mandates by regulatory agencies, may completely outweigh the cost disadvantage of not using the cheapest, lowest fidelity facility that can actually train a specific task or set of tasks. This means that there is no unique answer to the question of how much fidelity is required — or the best — for training a given task. This report, therefore, tries to do the following:

1. Outline a framework for the logical selection of training simulator facilities with guidance for making the various tradeoffs.
2. Address the question of how much fidelity is required to train a given flight phase in isolation.

A comprehensive set of this information would allow an agency to synthesize the overall system for its own particular situation; of course, the results of this effort were not that extensive. Some of the ideas outlined above will be elaborated on with the objective of defining some terminology and hopefully focusing attention on the primary questions addressed by the Working Group.

Assume that missions (M1, M2, etc.) of an aircraft A can be divided into flight phases FP1, FP2, etc. (see Fig. 1). The question is — what is required to train each individual flight phase? The physical facility would depend on at least the pilot experience/background and the instruction technique used. Figure 2 illustrates this idea. Instruction technique 1 (I1) with hardware 1 (H1) or I2 with H2 can be used to teach flight phase 1 (FP1) to pilots with background 1 (P1), and I3 with H3, or I4 with H4, can be used to teach the same FP1, but with pilots with background 2 (P2).

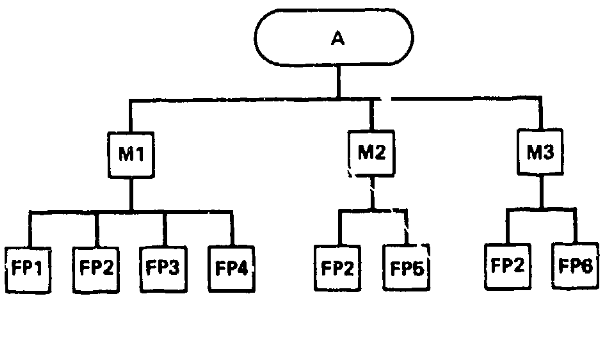

Fig. 1 Breakdown of missions into flight phases

Ignoring for the present the problem discussed earlier of how pilots and flight phases should be mixed, the first problem is how to define the best H1 for I1 and P1, H2 for I2 and P1, etc., where the quality for "best" may be cost, versatility (i.e., compatibility with other FPs, or Is, or Ps), or even availability (i.e., technically achievable simulator hardware).

Section 2 discusses in some detail the problem of breaking down a flight phase into tasks and defining an instruction method, and the tradeoffs in synthesizing a training facility for the particular circumstances of the interested organization.

Once the tasks to be learned and the training techniques to be used have been defined, the cues for objective fidelity can be defined. In selected areas of equipment cues, such as cockpit instrumentation, control panel and system operation, and cockpit hardware, this fidelity can be easily ascertained. In areas of environmental cues, such as visual scenes or motion cuing, extensive data concerning human

physiology and cue perception are required to permit rational decisionmaking. Unfortunately, there are two problems:

a. The knowledge of human physiology is insufficient to determine how much objective fidelity is required to achieve a given level of perceptual fidelty. A review of the present state of the art is given in Section 3 for the topic of sensory mechanisms relevant to motion fidelity, but specifically excluding consideration of the physiological factors not involved in motion senses, including visually induced motion sensations.

b. A high level of fidelity for perceptual cuing is not necessarily required for training, since some degradation in the cuing quality may still allow adequate transfer of training. This topic also is addressed in Section 2. The data in the research literature generally show that simulators can be effective for training, but there is very little specific data on the minimum perceptual fidelity for effective training. There are no universally applicable statements — some training tasks need high equipment fidelity but can tolerate low environmental fidelity; other tasks require closer to the opposite. A review of some of the more clearcut distinctions is presented in Section 2.

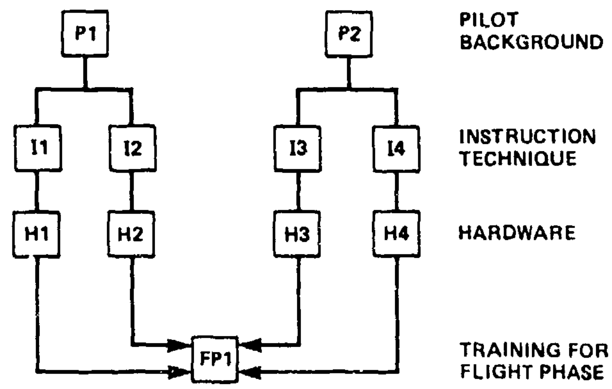

Fig. 2 Alternative training for a particular flight phase

A related problem discussed at length in Section 2 is the problem of just how the training effectiveness of a simulator should be assessed. Many approaches have been proposed and used in the literature. The most appropriate concept is the transfer of training (TOT) experimental paradigm which seeks to determine the extent to which training undertaken in a ground training device or simulator is successfully carried over to the flight situation. Another useful measure which can be computed from data obtained using the TOT paradigm is the training effectiveness ratio (TER). This ratio takes into account not only the number of aircraft hours saved, but also the number of simulator hours used to achieve the savings; thus, the formula is easily adaptable to estimating cost savings. The most appropriate, and the one recommended in this report, is based on transfer of training, a useful measure of which is the TER.

Given that the training specialist can indeed define the tasks that he wants trained on a simulator, the simulator technologist could probably do a reasonable job of translating the aircraft and flight phase definition into hardware characteristics that would provide a simulation with reasonably high objective fidelity (match the aircraft) and, with the help of the physiologist, high perceptual fidelity. Lacking clearcut physiological data, he could simply specify the best motion, visual, math model, etc., available. This, of course, is generally what happens today, but unfortunately leaves open the question of how much of these high-fidelity characteristics could be given up while still achieving acceptable transfer of training. In this study this question was an insurmountable block; the answers just do not exist. It was therefore rationalized that a survey of perceptual characteristics and simulator technology should be performed using high perceptual fidelity as the benchmark. This was done on the assumption that high perceptual fidelity at least defines a sufficiency of cuing, and it is reasonable to expect unity transfer of training with perfect perceptual fidelity; hence, defining simulator characteristics for perfect perceptual fidelity should be a useful benchmark for the training simulator developer.

Once the required perceptual cues have been defined in sufficient detail, they could be translated into physical hardware (and software) characteristics that will allow these cues to be provided. For this to be done it is necessary to have well-defined parameters on which to base these physical qualities. Section 4 addresses the subject of parameters that can be used to quantify simulator physical characteristics. Examples of the extent of documentation of these qualities were determined for some existing facilities, and examples are provided in the appendices to illustrate some of the currently best achievable characteristics. These qualities are also related to the quality needed for high objective fidelity and some existing deficiencies are pointed out.

1.3 Report Structure

Following this introduction, the report has four sections and four appendices.

Section 2 presents the training specialists' viewpoints on fidelity of simulators. The corresponding appendix A presents a survey of training simulator assessment methods.

Section 3 presents an overview of pilot cuing mechanisms, but is limited in scope to the mechanisms relative to simulator motion cues, including those induced by visual effects.

Section 4 presents the simulator technologists' assessments of existing motion, visual and computer model technology, discusses those characteristics that could be expected to provide high perceptual fidelity, and indicates where current limitations exist. Related appendices provide data on physical characteristics of existing facilities (appendix B), a survey of pilot opinions of existing training simulator facilities (appendix C), and a more detailed review of the technology of visual systems (appendix D).

Section 5 presents the Working Group's overall conclusions and reiterates the recommendations from Sections 2, 3, and 4.

2. PILOT TRAINING

In addressing the question of fidelity requirements for pilot training simulators, it became apparent that this issue was symptomatic of two much broader problems: first, the process whereby training requirements are translated into simulator design requirements and, second, the process whereby the effectiveness of the simulator within the training system is assessed. This section of the report is broken down into four subsections. The first deals with the issue of simulator fidelity and attempts to show that simulator design requirements should be based on more than obtaining a close replication of the aircraft. The second subsection presents an alternative approach to the definition of simulator design requirements, while the third considers the assessment of simulator training effectiveness. The last subsection presents a brief summary of the key points and makes recommendations for the future. One report prepared during the Working Group efforts is included as an appendix. This report provides a review of alternative simulator assessment procedures (appendix A).

2.1 The Issue of Simulator Fidelity

Historically, simulators have been designed and manufactured under the concept that the effectiveness of a device can be equated to its realism. The goal has been to make the simulator equivalent to the aircraft to whatever degree possible. Such an approach to simulator design has been widely accepted for a number of reasons. First, it is a relatively simple matter to state design requirements. The aircraft and its flight dynamics represent a reasonably well-defined model about which to define simulator performance requirements. Second, it is relatively simplistic from the standpoint of evaluation. It is a straightforward procedure to have an experienced pilot "fly" the simulator and make a judgment concerning its perceived equivalence to the aircraft. Third, it seems a necessity from the viewpoint of user acceptance. Since simulators are touted as replicates of the aircraft on the ground, it is small wonder that devices which fail to meet these expectations will be considered ineffective.

Despite these reasons for pursuing a design goal of maximum simulator fidelity, there are other considerations that seriously question the desirability of such an approach. One of the more important of these is cost. Increases in simulation fidelity typically lead to increases in cost. Advances in simulation technology have made available a wide variety of subsystems designed to increase the realism of the device. Wide field-of-view (FOV) visual systems, six-degree-of-freedom platform motion systems, g-seats and g-suits are typical of such fidelity-oriented hardware which have greatly increased not only procurement costs, but operations and maintenance costs as well. Second, there are technology limitations that currently limit the extent to which the ultimate in realism can be obtained. The airplane dynamically moves in three-dimensional space, while the simulator is bolted to the floor, so physical limitations prevent the full range of onset and sustained acceleration cues from being realistically simulated. Likewise, there are currently no visual systems capable of simulating the external visual environment to the level of detail found in the real world. Third, there are research data indicating that, for many situations, high fidelity simulation is not a necessary ingredient for effective training. Simulators of marginal fidelity, if properly used, have been shown to be highly effective training devices (Ref. 2).

Thus, the user is placed in the dilemma of deciding how much fidelity is necessary. Before attempting to sort out the dimensions that must be considered, it is first necessary to make certain assumptions regarding the role of simulation in flying training. The goal of flying training programs, whether civilian or military, is to initially train and subsequently maintain the necessary skills for safe and effective airborne operations. The role of flight simulation must consequently be considered in terms of its relationship to this goal. Flight simulation should be developed and utilized within the training program only if it can be shown to make a positive contribution to the fulfillment of training and the maintenance of flying skill. As intuitively valid as this assumption may appear, its consequences are often overlooked in the development and evaluation of flight simulator hardware and software programs.

The most obvious consequence is that simulator design requirements are a direct function of training needs. The projected role of the simulator in the training system should specify those objectives to be accomplished in ground training devices. Such anticipated training objectives should form the groundwork from which actual design requirements are specified. This approach is in contrast to the definition of requirements in terms that the simulator replicate the aircraft to whatever degree possible. Although projected ground training requirements may specify a device with a full mission capability, it is rarely the case that full fidelity cuing is necessary. A cue becomes essential only if it is a necessary condition for the fulfillment of a specific training objective.

An excellent example of differences in cuing requirements is given in tradeoffs between equipment cue fidelity and environmental cue fidelity where, as defined in Section 1, equipment cue fidelity refers to the physical correspondence between simulator and aircraft in terms of cockpit layout, instruments, controls, etc., while environmental cue fidelity refers to correspondence of the cues due to flight. As Fig. 3 shows, while it is generally expected that training simulators should possess high equipment and environmental cue fidelity, there also exist effective training devices that do not possess high fidelity in either dimension. At one extreme are cockpit familiarization and procedures trainers which have high equipment cue fidelity and low environmental cue fidelity. Such devices play an important role in initial and conversion training. At the opposite extreme are research simulators having high environmental cue fidelity but low equipment cue fidelity. Such devices have been shown to have the ability to train pilots in the handling characteristics of new aircraft types. There are also effective training media with both limited equipment and environmental cue fidelity. For example, academic instruction and various learning center media can provide effective training (Ref. 3). The conclusion is that high fidelity per se, whether equipment or environmental, may not be necessary for effective training. Instead, the critical dimension is whether or not the device capabilities will support specific training objectives. The key ingredient is that the training device simulates those cues that are necessary for effective learning of specific skills.

A second consequence of basing design requirements on high fidelity concerns the utilization of the simulator in the flying training program. The high fidelity model leads to the concept that the simulator is to be used like an aircraft, and therefore the student should fly a simulator mission in the same

manner he would fly an aircraft mission. Since it is well accepted that the aircraft presents a very poor learning environment, a much more effective alternative is designation of the flight simulator as a training device, which is indeed different from the aircraft. This enables the introduction of different training concepts, thereby enhancing the effectiveness of the training. Some of the major benefits are: (1) more control over the training task and the training environment; (2) an opportunity for more detailed and more objective assessment of performance; and (3) greater flexibility in terms of the ability to vary the content, order, repetition, and timing of training elements. In order to make the fullest use of these benefits, the user must be prepared to depart from the training procedures developed for airborne training.

Thus far, an attempt has been made to show that use of fidelity as a means of stating simulator design requirements is inappropriate. If one accepts the premise that the value of a flight simulator depends on its impact on subsequent airborne performance, it follows that its design requirements should depend on those training objectives it is intended to fulfill. Thus, fidelity requirements for visual and motion simulation cannot be determined strictly from the physical and dynamic models of the aircraft and the environment in which it operates. Of greater importance is a clear statement of the intended role of the simulator within the training system and the specific training objectives it will be designed to fulfill. Only when these are clearly defined does the question of fidelity requirements become appropriate. The following subsection is devoted to the development of the process whereby training device requirements can be systematically defined.

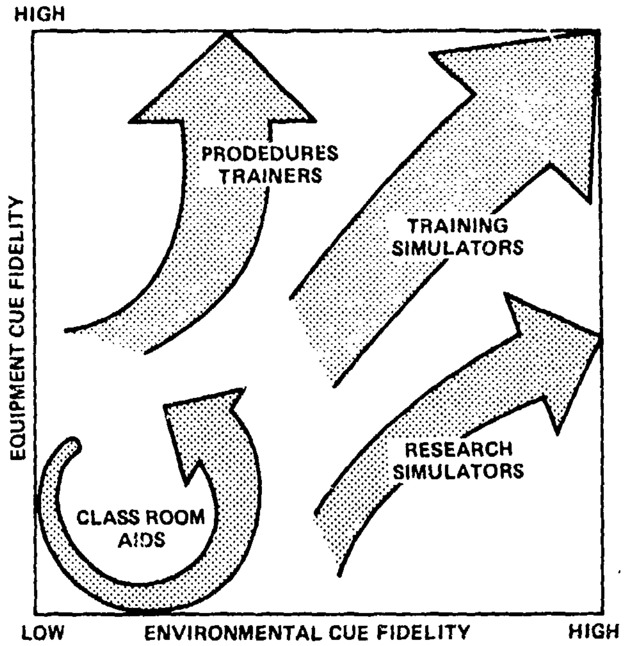

Fig. 3 Tradeoff between equipment and environmental cue fidelity

2.2 Definition of Simulator Requirements

2.2.1 Interrelationships

The previous introductory remarks attempted to show that the fidelity model is often an inappropriate means of defining simulator performance requirements. It fails to take into account a number of factors that relate to the role and function of the simulator in the flying training program. An accurate definition of simulator requirements can be accomplished only after careful consideration of fairly global factors including:

1. Operational mission requirements

2. Training system concept which will support the operations mission

3. Projected role of the flight simulator in that training system

In Fig. 4, an attempt is made to illustrate those factors that should be considered when defining simulator requirements. At the top of the diagram is the simple representation of procedures for the analysis of the tasks to be performed and the definition of training requirements. The model emphasizes that a number of detailed and time-consuming stages have to precede decisions regarding the nature of the training device to be used. The second stage, in the center of the diagram, is often ignored. The decision to develop and utilize a simulation system raises questions about the means of introducing and managing these associated elements in the training regime. The way in which these elements are handled may be altered by the presence of computer-based media, e.g., the use of computer-assisted learning. The third stage, at the bottom of the figure, looks at the characteristics of the flight simulator that may have an influence on the effectiveness of the device as a training vehicle. The development of simulator requirements by following a procedure that moves from the top to the bottom of the diagram is the recommended approach. In practice, however, it is often the case that emphasis is placed on work in the bottom segment of the diagram with little attention being given to the other two elements.

2.2.2 Definition of operational mission requirements

The analysis process must always begin with the aircraft in terms of its operational mission requirements. The goal of the mission analysis is to completely define the duties and responsibilities of each crew member during an operational mission. To aid in such an analysis, it is usually helpful to construct representative operational mission scenarios wherein the full capabilities of the aircraft and its crew are exercised Various contingencies should also be included (i.e., activities required as a result of inflight emergencies, diversions due to weather, reactions to ground threats, unique visual requirements relating to the terrain, etc.). Using these scenarios as a baseline, there are available a wide variety of function/task analysis procedures for further describing the duties of each crew member. For each task to be accomplished, information should include:

1. Relevant conditions under which the task is to be performed

2. Cuing information necessary for the successful completion of the task

3. Procedures involved in the successful execution of the task

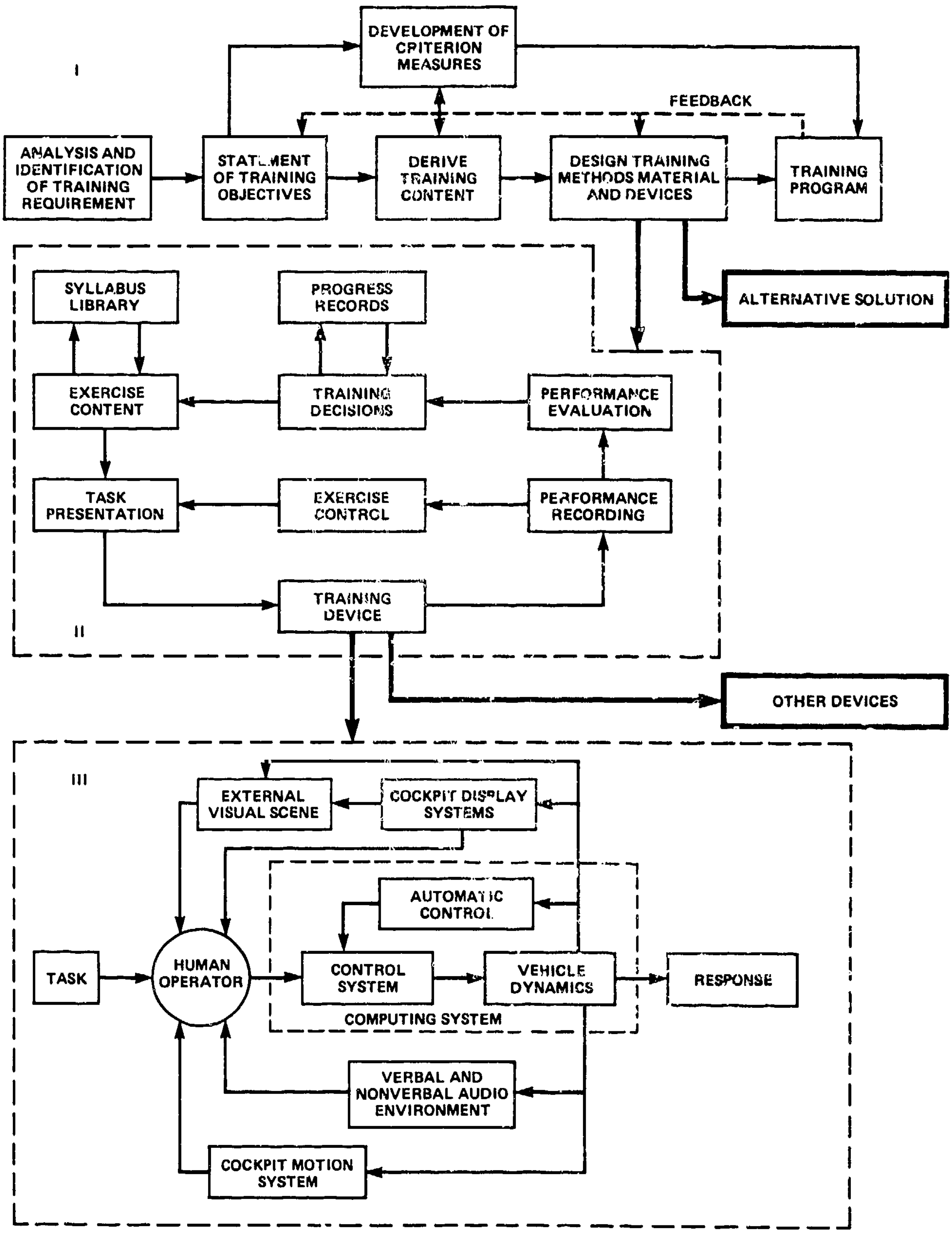

Fig. 4 Flow diagram for definition of simulator requirements

4. Criteria for determining that the task was successfully accomplished

Such information is of value in subsequent development of the training system and in specification of the required training devices.

2.2.3 Definition of training system concept

Successful analysis of the operational mission requirements should lead to a clear statement of training requirements. The ultimate aim of the training system is to ensure that these requirements are initially met and that subsequent performance is maintained at a high level of proficiency. While such requirements define those tasks that the aircrew must be able to perform for effective airborne operations, other factors must be considered before specific training objectives are defined and the content of the training system determined. One factor is the skill level of entry crew members. The skill level of recently graduated pilots will differ greatly from the pilot with several tours in an operational aircraft, and therefore, such diversity must be considered in the design of the training system. Likewise, factors such as pilot input, operational regulations, and economic constraints all have a significant impact and usually contribute to the definition of boundaries or limitations wherein the training system must be developed.

Having determined the training requirements, training objectives are defined and two actions carried out. First, the content of the training syllabus must be defined in terms of statements indicating what the trained person is expected to be able to do, under what conditions, and to what standard of proficiency. Second, criteria measures must be developed upon which to base course examinations and proficiency tests. With these actions completed, decisions can be made about design of the training system, training methods to be used, and training devices needed. Systematic procedures have been developed for accomplishing these tasks. Experience with the Systems Approach to Training (SAT) or Instructional Systems Development (ISD) has shown that such procedures can be of great value to the development of new training systems as well as the improvement of existing programs.

A critical aspect in the development of the training system and of relevance to the present paper is the selection of training media. In an examination of the application of ISD in the USAF, Miller, Swink, and McKenzie (Ref. 4) concluded that premature commitment to specific training media represented a major problem. Oftentimes, this led to the situation of the device driving the training requirement, rather than the training requirement driving selection of the media. Unfortunately, the ISD model per se provides no clear guidelines for selection of training media. Eddowes (Ref. 5) attempted to apply cognitive principles to the acquisition of flying skill and subsequently developed a concept for multimedia training programs which appears to have application in the present context. The objective is to match the student pilot's level of attainment with the complexity and representativeness of the training task environment. It is based on the observation that a significant portion of flight instruction can be presented more effectively in places other than the cockpit. The building-block approach to skill acquisition offers the obvious economy of using the simplest and least expensive training aid at any stage of training.

2.2.4 Role of the flight simulator in the training system

Consideration of the intended role of the flight simulator and past experience with similar training tasks should provide a fair picture of the scope of training objectives which a projected device would support. At this point, logistical factors such as projected student loads, the number of training locations, etc., must be taken into account so that tradeoffs between different arrays of devices can be considered. Perhaps the major tradeoff is between an array of part-task trainers and a full-mission device. To a large extent, the desirability of each approach will depend on the complexity of the aircraft to be simulated. As the complexity of the aircraft increases, either in terms of its number of roles or the size of its aircrew, its diversity of training requirements greatly increases. The result is that, in practice, the full-mission capabilities of a simulator are rarely used. If resources permit, training in an array of part-task devices followed by a demonstration of proficiency in the full-mission situation, either simulator or aircraft, may produce the most efficient training system.

Regardless of the final array of training media, it is essential that each is characterized in terms of the training objectives it is intended to fulfill. Thus, the requirements for flight simulation should be stated in terms of its projected role and intended use in the training system. It is only at this point that the question of fidelity becomes important. The critical issue is to decide on the degree of realism necessary for specific training objectives. In other words, for each training task, what are the necessary kinesthetic and visual cues? To some extent, the initial mission analyses should be helpful in providing such information. Likewise, research data should be of value in determining whether certain cues are essential for training. Although there is much data on a global level that simulator training can be effective, there is little data concerning minimum cuing requirements essential for training (Ref. 2).

Discussion to this point should make it clear that the flight simulator is only a part of the training system. Its role is determined by its relationship to the other elements of the training system and therefore cannot be considered as an independent and autonomous entity. Unfortunately, in practice there has been a strong temptation to ignore these interdependencies. Miller et al. (Ref. 4) concluded that oftentimes there was little correspondence between actual training requirements and training device functional capabilities. In fact, it often occurred that devices tended to drive the structure of training and that maximum fidelity capabilities available, rather than the minimum required for effective training, became the specification.

To correct these problems and to provide a clear definition of the intended role of the flight simulator in the training system, two questions must be answered. What are the expected or required outcomes that should result from the use of simulation? What are the training objectives the simulator should be capable of accomplishing? If one accepts the least-cost, sequenced, multimedia approach to training system development, it would follow that the goal would be to provide as much effective ground training as possible. However, existing policy may dictate that the simulator be used for only a limited scope of tasks. In any case, decisions regarding the projected role of the simulator in the training system should

drive the design requirements. Training capabilities of the simulator should be closely matched to its envisioned role in training. It makes little sense to require full dynamic simulation if the device is to be used only for cockpit familiarization.

The research data base regarding the minimum cuing requirements for effective training is quite limited. It is clear, however, that full-fidelity simulation is not an essential ingredient for effective training, and that fidelity considerations become relevant only in relation to the training objectives a device is intended to support. If more emphasis were placed on determining and specifying training requirements and using these to greater effect during procurement, the following changes in the acquisition cycle could be envisaged:

1. There would be less of a temptation to conclude that a simulator is the only answer. At present, manufacturers offer simulators because simulators are specified. If the requirements were written in terms of a description of the training required and the levels of proficiency that should be achieved, both user and supplier would be given the opportunity to analyze the training requirement and agree on the training device they considered best fitted the requirement. In other words, both parties would be forced to think about training aims.

2. Providing a requirement oriented more toward training than technical detail would produce readily identifiable training requirements at a stage which would allow them to be used as the basis for acceptance criteria. The current assessment procedures would thus be capable of being extended to allow the device to be assessed in terms of its ability to provide the training required.

3. The gap between the working simulator and its use as a functional training simulator would be reduced. Present procurement processes can result in the provision of a device that meets the technical specification, but may be unable to make an immediate contribution to the training program for which it was purchased. For example, a device may have the facility to store and have available on call a number of preprogrammed exercises, or it may have the capability to undertake a range of performance-measuring operations. However, facilities such as these can only contribute to training when they contain the necessary training tasks or can analyze the appropriate performance parameters. Until this is done the facilities will not be operational and may remain unused. The gap between the working and functional devices can grow larger as the time and knowledge required to bring the facilities on line increases. If, however, a requirement is based on specific training objectives, responsibility would fall much more on the supplier to provide a device that was comprised of operational elements at the point of acceptance.

The development process of the flight training simulator should involve four disciplines: a) training developer, b) engineer, c) physiologist, and d) pilot/trainer. Each of these backgrounds provides inputs to the design dimensions which must be considered to achieve the ultimate objective of training pilots to perform aircraft maneuvers. The model proposed in Fig. 4 provides an indication of the points at which the four disciplines have key responsibilities. These responsibilities will occur within the three blocks and also at the interfaces between them.

The pilot/trainer input should be considered as an instrumental part of the analyses process (I) and the validation process (II). As a member of the training developer analysis team (I), his input should drive the training objective to be based on operational requirements. His participation in other phases of the model, until he re-enters at the validation phase, is in the role of a consultant operational expert.

The training developer and the physiologist interact to describe the training objective in terms of perceptual cues. The physiologist functions to transform the training objectives into quantifiable values which are adequate for stimulating the human sensory process. Thus, the training facility objectives are specified in thresholds, washout rate (adaptation cycles), amplitude, frequency, etc. Next, the training developer and pilot interact to define the instructional and performance assessment features required. The engineers then design the system (block III) to reproduce required responses as defined by the physiologist and the instructional facilities specified by the pilot/trainer.

In the process of validating the device, fidelity can again become a major issue. Typically, the process consists of the following steps:

1. The pilot/trainer evaluates feel and acceptability based on his concept of fidelity (perceptual fidelity).

2. The engineers measure the extent to which the simulator faithfully reproduces the vehicle dynamics (objective fidelity).

3. The physiologist is not typically involved, yet should be. In accordance with the philosophy propounded above, that high fidelity is an unsatisfactory criterion, steps 1 and 2 should be replaced by checks to see that the perceptual cues defined by the physiologist were indeed achieved. He would measure how effective the simulator response characteristics were in providing adequate stimuli for the human operator to perform the chosen tasks.

4. The training developer will validate the simulator against its training objectives using the training effectiveness paradigm. Quantitative measures applied to the individual elements of the training syllabus will provide an indication of those subtasks for which the training system is effective and those subtasks for which some modification of the system is necessary. An informative example of this procedure is described by Holman (Ref. 6). Unfortunately, the current TER methodology is only sensitive to rather global training effectiveness measures and will not typically answer detailed specific system design questions. Thus, if the TER is unacceptably low, steps 1 and 2 have to be resorted to so that aspects of low fidelity can be identified and perhaps improved. This, of course, is why the high-fidelity model is often used as the design goal in the first place. Step 3 above is the key to a non-high-fidelity approach and must be given more emphasis.

It is critical to recognize that each of the disciplines has an essential role in the development and employment of a flight training simulator. These roles must be complementary in nature, and at no time should the different disciplines become adversaries. A cohesive, properly balanced, design team must be employed to ensure that a simulator developed as a result of the ISD process is an effective training device.

2.2.5 Research findings

The research literature relating to the value of flight simulators is extensive. General reviews of the simulator training literature are found in Orlansky and String (Ref. 7), and Rolfe (Ref. 8); a review of current simulator substitution practices in Diehl and Ryan (Ref. 9); and a review of the training effectiveness of visual and motion simulation by Waag (Ref. 2). In summarizing this literature, the following conclusions can be drawn:

1. The flight simulator is an effective means of teaching and maintaining aircrew skills. This assessment is based on a limited number of objective and controlled studies of simulator training effectiveness, the majority of which were undertaken in relation to initial training, and on a large body of information derived from trials and evaluations.

2. Substantial amounts of time in the air can be replaced by the use of simulators.

3. Skill training-and-maintaining activities will require approximately the same amount of time in the simulator as in the air. If time savings are achieved, their most likely source will be in the reduction of the nonproductive time associated with airborne training, e.g., time spent positioning in order that the training detail can commence.

4. The ease with which tasks can be learned in the flight simulator and transferred to the aircraft varies with the nature of the task. Procedural skills will generally transfer readily but will be forgotten unless practiced regularly. Perceptual motor skills transfer less completely because they are more susceptible to imperfections in the simulation of dynamic factors of environmental fidelity such as motion, visual, and kinesthetic cues and control forces. Nevertheless, while the level of transfer may be lower, rapid adaptation appears to take place in the flight environment. Simulators for maintaining procedural skills will be easier to provide than simulators to assist in the retention of perceptual-motor skill.

5. The effects of simulator training are most apparent in the critical period immediately after the student moves from simulator to aircraft. Simulator-trained students are likely to show high levels of proficiency on initial transfer to the aircraft, with the result that student and instructor confidence is enhanced from the outset.

6. Training effectiveness is not determined solely by the appropriateness of the training device to the training task. How the device is used can influence its effectiveness to an equal or greater extent. One very pertinent example is the strategy employed for allocating training time in the simulator. The bulk of controlled studies of simulator training show that simulators are most effective when the student is allowed as much time as he needs (with some maximum limit) to reach a criterion standard of performance. This strategy contrasts with the more frequently encountered policy of allocating fixed amounts of time.

7. Differences between the training and operational equipment and environment may be essential in order to achieve the most effective training. First, training effectiveness can be improved by reducing the level of complexity in the training device so that the student can concentrate on those elements which are relevant to the task being trained. There is a range of studies which shows that part-task training devices, systems, and procedures trainers are very effective, within the limits of their defined roles. Second, changes to the equipment may be necessary to provide the student with better knowledge of his performance, for example, by allowing manipulation of the training task by freeze and replay. Third, it can be beneficial if, particularly during the initial stages of training, instruction can take place in a more stress-free environment than that encountered in flight.

8. Motivation is a key element in achieving effective training in a ground trainer. Effectiveness is highest when the instructor realizes and espouses the usefulness and relevance of the device even though he or she may be required to teach around faulty capabilities or features. Students tend to reflect instructor attitudes. Further, where recurrent or refresher training is being provided to experienced trainees, with or without instructor, an element of competition, or a comparative such as a probability of success in combat simulations, tends to motivate trainees to better and faster learning.

9. The degree of realism of simulation required will depend on the nature of the task, the level of experience of the students, and the level of proficiency the student is expected to possess at the end of training in the device. For unskilled students there is considerable evidence that simple devices can be very effective for teaching basic procedures and drills. While far more complex devices may be required when the task is to develop and maintain the skills of operational aircrew, there may be valid reasons for employing some form of part-task trainer rather than a full simulation.

10. The bulk of research data on the use of visual simulation concerns its effectiveness for transition training. With few exceptions, the overwhelming finding has been that visual tasks learned in the simulator show positive transfer to the aircraft. Successful use of visual simulation has been demonstrated for training fighter and transport fixed-wing aircraft as well as for rotary-wing aircraft. Few studies have been accomplished for tasks other than transition. This is due to the only recent availability of wide-angle visual systems necessary to perform certain tasks. Nonetheless, data thus far suggest that transfer can be obtained in visual tasks such as formation,

flying, refueling, and surface-attack weapons delivery. For aerobatic and air combat skills, only a modest amount of transfer has been demonstrated.

11. There is insufficient research data to make conclusive statements regarding the value of motion in the training context. It is noted that some research studies involving tracking tasks do show that the presence of good motion simulation produces operator control responses that correspond more closely to those recorded in the flight situation. However, such findings cannot be directly translated to mean that motion is essential for training simulators for conventional flight tasks. A more valid approach is to employ motion simulation when an analysis of the training tasks shows that motion is needed because it:

    a) Provides those cues which are necessary if the student is to learn to perform the task correctly

    b) Introduces features of the flying environment which can degrade performance and thus need to be experienced so that compensatory strategies can be developed

12. Training effectiveness studies of motion simulation to date have only addressed the contributions of platform motion. In no instance has training in centerline thrust aircraft been significantly enhanced by the addition of the limited platform motion capabilities available at the time. For training in other types of aircraft, study is needed to support current opinion that motion is essential. Alternative devices for simulating motion cues, i.e., g-seats, g-suits, and stick-shakers are being evaluated, but at this time insufficient evidence is available to make a statement on their efficacy.

While there is a long way to go to define all characteristics of a good training simulator, existing research data provide a basis for making some relevant generalizations:

1. The features of a specific training device should support all planned training objectives. The objective is to maximize the effectiveness of training in the device and reduce requirements for altering a training program because of device limitations (i.e., reduce "training around").

2. Only the cues judged to be necessary to achieve the learning objectives should be provided. As noted in other sections of this report, some objective data are available in the areas of motion and visual cuing, but much more is required.

3. A simulator that is to be used for training visual flying tasks must include a visual system. The degree to which the visual system must reflect real-world scenery is highly task-dependent.

4. Provisions should be included for the trainee to respond in a correct fashion to the cues provided.

5. Performance measurement capabilities relevant to the learning process should be provided.

6. Sufficient software control and data storage should be provided to support the use of structured exercises that may resemble flight sorties.

7. Capabilities should be provided for exercising operational control of the training program, i.e., freeze and reset, record and replay, automatic demonstrations, etc.

8. Student learning is enhanced by knowledge of results; thus, a capability to provide performance feedback to the student is required.

9. Sound provides some helpful cues in pilot training and should be included; however, in most cases these cues can be satisfied with relatively low fidelity but extremely timely executions. It is readily admitted that little research data are available to support this position.

10. A good simulator system requires very careful definition of the computational system because it is the key for integration of the device.

11. The needs of the flight simulator instructor must be recognized and a suitable instructor station provided.

2.3 Assessment of Simulator Training Effectiveness

In addition to defining training-device requirements, an associated but separate activity is that of determining what contribution the flight simulator makes to training, i.e., validating that the device does what it was bought to do. The term usually employed to describe this process is training effectiveness, and while this term is frequently encountered in the literature on flight simulation for training, it is a topic that is subject to misunderstanding and abuse. Training effectiveness should be concerned with determining whether a training device has an effect, either positive or negative, on a trainee's subsequent performance. It is often the case, however, that attempts to determine training effectiveness rely on user opinion, detailed assessment of the physical and dynamic fidelity of the simulation in comparison with the aircraft, or the measurement of how much the device is used. None of these measures is by itself a reliable indicant of training effectiveness; user opinion assumes that the user is able to assess accurately how much has been learned from the device; assessment of simulator fidelity gives only an indication of a device's realism and not its training capability; and the measurement of how much a simulator is used gives no indication if the device is being used effectively for all or part of the time.

Of the different approaches to the evaluation of simulator training effectiveness, the transfer of training methodology seems most appropriate [appendix A and Caro (Ref. 10)]. Transfer of training occurs whenever the existence of a previously learned behavior and skill has an influence on the acquisition, performance, or relearning of a second behavior or skill. Thus, if a behavior is learned in an aircraft simulator and the existence of that behavior, or the fact of its having been learned, has an influence on

the subsequent performance or relearning of behavior in an aircraft, transfer is said to have occurred. In its simplest form, the transfer of training model involves two groups of trainees: an experimental group that receives simulator training prior to further training, or performance tasking, in the aircraft; and a control group that receives all of its training in the aircraft. Comparisons of performance in the aircraft enable conclusions to be drawn about the effectiveness of training. One measure frequently used is the Transfer Effectiveness Ratio (TER) which gives an indication of efficiency of the training device. It is the ratio of the number of aircraft hours saved to the number of hours required in the simulator. A ratio of 1.0 indicates that the training device is as efficient as the aircraft.

While such procedures do provide information on the effectiveness of simulator training, they do not directly indicate the value of the simulator per se. Such indices reflect the effectiveness of the device only within the context of how it is being used. It is impossible to completely separate the characteristics of the training device from the manner in which it is used. There are excellent examples in the literature wherein the effectiveness of existing equipment was enhanced solely through changes in how the device was being utilized. Such findings further emphasize the need to consider the flight simulator as an integral part of the training system designed to fulfill certain training objectives rather than an independent piece of hardware designed to replicate the aircraft.

A further question remains as to whether training effectiveness is the only criterion. Inevitably there is the question of cost. Even though a device may be capable of providing effective training, will that training be cost-effective? Orlansky and String (Ref. 7) have recommended that increased emphasis be given to cost-effectiveness criteria for all aspects of flying training. Evaluations of major training media such as part-task trainers, cockpit procedure trainers, etc., as well as major simulator components such as motion systems, visual systems, etc., should include estimates of their cost-effectiveness. Unfortunately, current cost-effectiveness models are applicable to situations wherein training effectiveness is equated with saved aircraft hours. Benefits to be derived from the utilization of flight simulators for tasks that cannot be practiced in the air have not been quantified.

2.4 Conclusions and Recommendations — Training

In conclusion, this section has emphasized the following points:

1. The role of the flight simulator must be considered in terms of its relationship to the overall goals of the training system, i.e., to the initial acquisition and subsequent maintenance of flying skills. Flight simulator development and utilization is warranted only if it makes a positive contribution to these goals.

2. Simulator design requirements should be driven by the training objectives that the device is intended to fulfill.

3. Specific cues should be simulated only if they are essential for the initial learning or subsequent maintenance of the intended training objectives. Fidelity requirements are thus dependent on the specific training objectives the device is intended to fulfil.

4. The existing literature on essential cuing requirements, particularly those provided by visual and motion systems, for specific training objectives, is quite limited. Nonetheless, the available data indicate that, of the two, visual cuing has a substantially greater potential for enhancing and extending the effectiveness of simulator training.

5. The transfer of training model is the most appropriate method for determining the effectiveness of simulator training; however, caution must be exercised since it is impossible to completely separate the quality of the hardware from the manner in which it is used. This observation reinforces the need to consider the simulator as an integral part of the training system and not as an independent or autonomous entity.

One of the major points just mentioned concerns the lack of research data. A key issue in any investigation is the extent to which the results have application beyond the immediate conditions of the study. This requires the investigator to have an understanding of the critical dimensions that may impact the study outcome and thereby generate a design that will maximize the generality of the results. Although it is known that factors such as aircraft type, pilot experience level, and type of task may affect the outcome, little attempt has been made to integrate these in some coherent fashion. Furthermore, there has been a failure to quantify the critical dimensions of motion and visual systems, except in the most rudimentary way (e.g., on vs. off, or day vs. night, etc.). In other words, there exist no quantifiable models of visual and motion simulation which enable testable hypotheses to be generated which might subsequently lead to some generalizable findings. Until recently, it has been difficult to quantify visual and motion system characteristics because of a lack of standardized definitions of the important characteristics; however, an AGARD Working Group has recently produced a report (Ref. 11) to do this for motion systems, and another group will produce a corresponding report for visual displays, probably during 1981. It should be noted that Ref. 11 is limited to defining the motion system capabilities, not how it is being used (i.e., the washout scheme, etc.). Until such models are developed and used, progress will occur in a haphazard fashion at best.

The following recommendations are made:

1. A major research effort should be initiated to determine minimum cuing requirements across the range of training objectives which can potentially be addressed in the simulation environment. Such an effort should not be constrained by current flight simulator practices, but should also address futuristic applications, such as full-mission combat simulation, tactics development and evaluation, etc.

2. Research should be expanded on cuing requirements for effective visual simulation, since such capabilities can greatly expand the ground training environment. There exists a need to develop

models of the visual environment wherein the relevant parameters can be identified and subsequently studied to determine their impact on simulator training effectiveness.

3. Procedures should be developed to bridge the gap between training objectives and specifying training device capabilities. It is recognized that training-requirement specification is an alternative to training-device specification, and it is recommended that a thorough study of the merits and drawbacks of the alternative procurement procedures be initiated.

4. Procedures for determining the training effectiveness of flight simulators should be applied and the results used for additional device procurement and design decisions. Studies should be initiated at two levels. First, attempts should be made to gather data on training effectiveness using the TER model, while ensuring sufficient quantitative definition of the facility so that the data can be generalized. Second, an effort should be commenced with the objective of deriving an assessment system that considers simulator/aircraft operating cost ratios and utilization rates.

5. Because of the wide scope and the extensive resources required for such research efforts, it is recommended that AGARD initiate and support a collaborative multinational effort using cross-disciplinary evaluation teams similar to those engaged in this Working Group. AGARD has already initiated action along these lines in relation to visual and motion systems. It is therefore recommended that effort be concentrated on the formulation of a Working Group to pursue the training effectiveness question.

3. PHYSIOLOGICAL FACTORS

This section is concerned with the sensory mechanisms relevant to simulator motion fidelity. It excludes consideration of the physiological factors not involved in motion senses. Its scope does not extend to the physiological bases for visual field tunneling or other high-g effects, for example. It similarly avoids direct consideration of the important psychological factors associated with validity of cockpit appearance, interpersonal relations between pilot and instructor, or motivation of the trainee.

The mere existence of a sensory signal, which can be detected by a pilot, guarantees neither that it will be relevant to training effectiveness nor that it will have any observable effect on pilot control strategy or performance in any specific task or with any particular vehicle. There is a paucity of existing, carefully documented, experimental results concerning the cues required for training effectiveness. Consequently, this section concentrates on a review of the literature concerning the influence of motion cues of various types, and of out-the-window (VFR) visual scenes, on pilot control strategies and performance. Nearly all of the studies involved continuous pilot control for tracking or disturbance regulation. Only a few cases have been investigated in which transient failure effects, such as control system or engine failures, were investigated with control of motion and visual cues. In general, provision of motion cues, with or without wide-field vision, shows increasing utility for tasks requiring lead compensation, multi-axis control, smooth manipulation, and ample time for scanning alternate displays.

A concerted effort has been made in recent years to incorporate motion cues into analytical models of the pilot for application to the problem of simulator specification, both for research and for training. The underlying goal has been to produce pilot models, sensitive to motion as well as visual cues, which could be tested to determine the importance or relevance of proposed motion cues for any particular combination of aircraft dynamics, maneuver type, and disturbance. The state of motion sensor models of the vestibular system and their application to the problem of closed-loop piloting is reviewed by Zacharias (Ref. 12). Significant extensions of the pilot optimal control model (OCM) to include motion effects have been achieved by Curry et al. (Ref. 13) and by Junker and Levison (Ref. 14). The Curry et al. report assumes that the dynamic response and noise characteristic of the vestibular sensors is represented in the Kalman estimator inherent to the pilot. Junker and Levison assume that, with motion, vehicle acceleration as well as velocity is observable by the pilot. Both efforts are reasonably successful in matching differences between motion and fixed-base pilot behavior discussed in Ref. 13. Borah et al. (Refs. 15, 16) have further extended the pilot model for spatial orientation (not for control) to include the influence of platform motion, wide visual-field displays, and tactile cues.

Two thorough reviews of the motion cue literature have recently appeared: Curry, Hoffman, and Young (Ref. 13, pages 7-18) summarize the experimental data concerning motion cue influences on pilot control and performance — and use the data as the basis for their model of pilot control. The recent extensive literature summary by Puig, Harris, and Ricard (Ref. 17, pages 27-54) goes beyond the Curry et al. report to consider the large number of motion/no-motion simulator studies in which performance or acceptability was the end-product, rather than control characteristics.

3.1 Motion Sensing Mechanisms

To appreciate the following material relating human motion-sensing capabilities to simulator performance requirements, it is necessary to have some understanding of the underlying physiological mechanisms. Even an elementary view of the sensory physiology relevant to this subject, however, is beyond the scope of this report. The reader is referred to Refs. 18, 19, and 20 for more detailed presentation. The following paragraphs merely summarize the roles played by the principal sensory mechanisms involved in motion detection and relevant to the flight simulator problem.

3.1.1 Semicircular canals

The semicircular canals, along with the otolith organs to be described below, comprise the balance mechanism in the inner ear, referred to as the nonauditory labyrinth, or the vestibular organs. The semicircular canals consist of three roughly orthogonal fluid-filled ducts in each ear. Each canal is normally sealed by a mechanism called the cupula, which contains the upper ends of hair cells and transduces minute pressure changes in the canals into neural signals to the central nervous system. Although the semicircular canals are fundamentally overdamped angular accelerometers, relying on the inertial properties of a ring of fluid to remain fixed as the head is rotated, their function is more analogous to that of rate gyros. For most of the frequencies involved in normal daily activity, the semicircular canals adequately signal the angular velocity of the head about any axis. At frequencies below 0.1 Hz, however, which are normally sustained only in man-made vehicles and are very common in airplanes, the semicircular canal signals are misleading. They no longer are representative of angular velocity but rather exhibit a phase lead that makes them closer to indications of angular accelerations at extremely low frequencies. The resulting illusion and disorientation problems from low-frequency canal signals are well known in aviation and are discussed at length by Gillingham (Ref. 21) and Benson (Ref. 22).

3.1.2 Otoliths

The otolith organs are located within the inner ear and play the role of linear accelerometers in the human internal inertial orientation system. Each labyrinth contains two such otolith organs. The utricle is oriented roughly in the horizontal plane with the head in its normal position, and the saccule is oriented primarily in the vertical plane. Each of these organs contains a membrane embedding calcium carbonate crystals which is only partially floated in its surrounding fluid. It is connected to its underlying structure by supporting cells and hair cells capable of detecting its motion. The dense membrane is analogous to the seismic mass of a linear accelerometer. The supporting cells are analogous to the restoring spring, and the hair cells to the displacement readout device on such an accelerometer. Like any linear accelerometer, the otolith organs are incapable of distinguishing between gravitational acceleration and linear acceleration with respect to inertial space. This in fact leads to a series of well-documented illusions including that of pitch-up during forward accelerations which is well known during catapult launches of aircraft from carriers.

3.1.3 Pressure sensors

In addition to the inertial force detection system of the otoliths, the entire supported mass of the body acts as a seismic mass that permits detection of orientation by means of tactile or somatosensory cues. These pressure cues, which form the basis for the feeling of "flying by the seat of the pants," consist of both surface tactile receptors in the outer layers of the skin and so-called "deep pressure sensors" located well below the surface. All of the somatosensory receptors are rapidly responding and normally give the first indication of a change in force or orientation. They are also all highly adaptive in nature, some with time constants of the order of tens of milliseconds and others with time constants of the order of seconds. Of importance for their use in simulation, however, is the common characteristic that their output tends to return to a reference level during sustained uniform pressure application (see Ref. 15 for a review).

3.1.4 Proprioceptive sensors

The relative positions of parts of the body, as well as their movements, are signaled by the proprioceptive and kinesthetic senses. These senses, which are analogous to the use of resolvers for angular orientation or strain gauges and length transducers for actuator measurements, signal limb, head, or trunk orientation to the central nervous system. Three basic types of sensory mechanisms are involved. The muscle spindles are parallel, adapting, length measurement mechanisms located within the muscle fibers. They normally signal both changes in muscle length and deviations from commanded or desired muscle length. The Golgi tendon organs, located in series with the main body of the muscle, signal muscle tension. The combination of muscle spindle and Golgi tendon organ outputs can be used to indicate the effort required to maintain the head or limb in a given orientation during aircraft motion. Multi-degree-of-freedom angular orientation at each of the joints is also signaled, in a relatively imprecise manner, by the joint angle receptors located in the joint capsules. Since the output of these receptors is also affected by pressure in the joint, they are not absolute indicators of joint angles. The combination of all the proprioceptive senses permits subjects to perceive body accelerations based on the biomechanical reactions of the head or limbs, whether or not these limbs actually move, by measuring either the force required to keep them stationary or the resulting motion.

3.1.5 Visual motion detection

Quite apart from those aspects of visual field presentation which lead to a cognitive sense of self-motion there is an elementary phenomenon known as "vection," in which self-motion sensations are created by uniform motion of a wide visual field. This phenomenon, which can induce linear or angular motion sensations is based primarily on the motion detection capabilities of the peripheral retina and relies upon wide-field multicontrast objects moving at uniform velocity. Color and high acuity are relatively unimportant for the generation of visually induced motion from peripheral visual field presentations. The foveal portion of the retina is the high-acuity, cone-filled, central part of the retina associated with accurate image scanning and recognition.

3.2 Basic Cuing Methodology

3.2.1 Platform motion

Dynamic response to semicircular canals — Since the semicircular canals only function as adequate transducers of angular velocity over a limited frequency range, it is not required that the simulator platform motion match aircraft motion other than within this range. In particular, the low-frequency characteristics of the semicircular canals, below approximately 0.1 Hz, indicate only acceleration and not velocity. It is possible to "wash out" platform motion at these low frequencies, thereby achieving some measure of adequate motion cues in a limited space. The entire notion of washout for limited-motion flight simulators rests on the presumption that the platform can be returned to some central or neutral position during periods when the aircraft would continue at a relatively constant or slowly changing velocity, without allowing the pilot to detect this motion disparity. The adequacy of such wash-out algorithms depends on an appropriate appreciation of the effective thresholds of the semicircular canals and their response to different combinations of accelerations and velocities. One approach is to attempt to match the vestibular system outputs from the simulator platform motion to those which would be achieved by the aircraft, at least to within the error bounds of the order of the semicircular canal thresholds.

Thresholds of the semicircular canals — Sensory system thresholds should not be thought of mechanistically as absolute values for stimulus detection. Rather they are more appropriately considered in an information theory sense, in which, under appropriate conditions, the longer a stimulus is applied, the greater the probability that it will be detected as a more than random deviation from the noisy "resting level" of the sensor. For example, a subject who is seated quietly in the dark may detect that he is rotated about a vertical when the angular acceleration imposed in a stepwise manner is as little as 0.1° to 0.2°/s^2, provided he is given a sufficiently long time to detect it. This leads to curves of detection time vs. acceleration level which range from the threshold levels of approximately 0.2°/s^2 to significantly larger acceleration which will go undetected for briefer periods of time. More realistic situations which account for the effects of pilot workload (increased thresholds, Hosman and Van der Vaart, Ref. 23), the presence of lighted elements in the cockpit (decreased threshold, Huang and Young, Ref. 24), and the superimposed vibration in the aircraft and simulator environment (minimal effects on threshold, although low-frequency vibrations do lengthen latencies to detection of angular acceleration, Ref. 25), lead to the following rules of thumb: Pilots might normally be expected to be insensitive to sustained accelerations as low as 0.2°/s^2; when the accelerations are of duration briefer than 5 sec, the total angular velocity change which they might not correctly detect can be as large as 2.0°/s. Ormsby (Ref. 26) deals with the issue of appropriate combinations of threshold measurements and the dynamic response of the semicircular canals to determine optimum motion wash-out algorithms.

Dynamic response to linear acceleration and tilt — The otolith organs appear to give a very rapid response when stimulated by sudden linear accelerations or tilt with respect to vertical. The perception of such motion or tilt, however, shows a considerable amount of dynamic lag unless it is confirmed by some

other cue, such as semicircular canal activity or vision. The relationship of perceived to actual linear velocity has been modeled as a simple third-order system, with a dominant long-time constant of 5 sec (Young and Meiry, Ref. 27). For stimulus frequencies near 0.4 Hz, the perception of linear motion is roughly in phase with the applied motion. Below 0.2 Hz increasing phase lead is shown, and the perception of linear velocity tends toward being in phase with the applied acceleration. At extremely low frequencies, below 0.1 Hz, adaptation effects come into play, and the magnitude of the perceived motion becomes less than that of the applied motion. This latter phenomenon allows one to wash out linear acceleration and tilt by slowly returning to a neutral position under the presumption that any steady-state orientation will eventually be taken as the vertical.

Thresholds of linear acceleration and tilt — Linear acceleration of sufficiently low levels will go undetected by the pilot, although no firm physiological basis for an absolute threshold exists. The information from the otolith organ apparently will not permit reliable perception of changes in acceleration below 0.005 g, regardless of its duration. More practical effective threshold values for lateral or fore-aft acceleration from a head-erect position are closer to 0.02 g. This is consistent with the ability to detect tilts from the vertical of about 1.5° to 2.0°. These threshold values can probably be doubled by the reduction or elimination of strong tactile cues, as by the use of unusual seat supports or superimposed vibration.

For brief periods of linear acceleration lasting less than 5 sec or so, the effective time to detect the acceleration decreases with increasing acceleration level. A useful rule of thumb is that changes in linear velocity less than approximately 22 cm/s are likely to go undetected in the horizontal plane (Melvill, Jones, and Young, Ref. 28, and Young and Meiry, Ref. 27).

Direction uncertainty for vertical acceleration — Although otolith organ sensory signals are available at apparently the same level of sensitivity for vertical as for horizontal acceleration, perception of motion along the vertical axis frequently shows an important ambiguity concerning direction. Threshold levels and time to detect are virtually identical to those for horizontal motion, yet subjects are frequently uncertain as to the direction of their velocity when accelerated in the vertical. It is tempting to attribute this uncertainty, as well as the "otolith blindspot," to the lack of human familiarity with orientations other than the head-erect position. In any event, the relevance to simulation is that it is easier to introduce undetectable false cues in the vertical axis than it is for linear acceleration along a horizontal axis.

Tilt as a means to simulate sustained acceleration — Since the graviceptors, including the otolith organs, are incapable of distinguishing between linear acceleration and orientation with respect to the vertical, it is common practice to substitute a steady pitch or roll attitude, which is easily achievable with limited platform motion, for sustained linear acceleration which is not achievable in a limited motion simulator. Despite an absence of firm experimental evidence to validate this practice, it is safe to make several generalizations about its applicability. The exact angle of pitch or roll is probably not critical, although ideally it should line up the net gravito-inertial acceleration vector with the vertical. This takes advantage of the fact that perception of the angle of orientation is considerably more precise than is perception of absolute acceleration levels. It is, however, very important that the rate of pitch or roll utilized in performing the g-tilt maneuver be such as to avoid the generation of inadvertent false rotation cues. Angular rates below semicircular canal thresholds are clearly acceptable, but if one is restricted to g-tilt maneuvers that rotate the cockpit at subthreshold rates, the time taken for the lateral acceleration to be washed out and substituted by g-tilt is excessively long and leads to intolerable simulator excursions. Compromises are generally achieved by rolling or pitching at slightly super-threshold rates to tilt angles less than ideally required and relying on the influence of visual cues to minimize the importance of the conflict.

3.2.2 Visually induced motion sensations

The practicality and increased availability of the wide FOV visual displays for flight simulation makes consideration of visually induced motion-vection particularly important. Effective circularvection or linearvection, based on uniform motion of a visual field, can, to a large extent, substitute for non-visual motion cues normally provided by platform motion. This section summarizes a few of the principal characteristics of visually induced motion sensations as related to requirements for flight simulation (Young, Ref. 29). It specifically excludes consideration of the use of content of the visual field and refers only to movement of otherwise meaningless contrast borders.

Field of view — Visually induced motion is particularly effective when the field of view is larger than 60°. The most effective stimulation has been achieved when the moving FOV is a full 180° field, although adequate motion cues have been achieved with 60° to 100° FOV in the horizontal, and approximately half that extent in the vertical. The motion in the central field appears to be relatively unimportant in generating visually induced motion and may, in fact, be eliminated without severely affecting the strength of vection.

Characteristics of the visual field — Vection is most effective when the visual field is one consisting of a number of high contrast borders, filling at least 30% of the FOV. Small objects occupying 1° to 3° in extent seem most effective. Brightness, high contrast, and uniform velocity are all important in increasing the effectiveness of visually induced motion and reducing the time delays to its onset.

Background versus foreground displays — Visually induced motion is difficult to achieve unless the moving visual field is presented as background, preferably distant information. Fixed objects in the background can completely destroy visually induced motion. On the other hand, fixed objects in the foreground, such as parts of the pilot's body, elements in his cockpit, frames in a windscreen, or the divisions between portions of a wide field display, do little to inhibit the development of visually induced motion. Blocked-out portions of the background up to several degrees in extent appear to be relatively unimportant in eliminating the visually induced motion effect. Head-fixed objects that might appear at optical infinity or at distances comparable to that of the moving display should be avoided if it is considered important to generate effective vection.

Rates of motion — Visually induced yaw is quite effective over the range of angular velocities up to approximately 60°/s. At yaw rates higher than 60°/s, the vection becomes "unsaturated"; the perception of self-rotation is less than that of field rotation, and both are sensed at once. At very high angular velocities, exceeding 100° to 200°/s, the visually induced motion sensation may completely disappear. For visually induced motion about the pitch or roll axis, the effect is normally a paradoxical one of pitch or roll rate, without a corresponding continuous change in pitch or roll angles. Thus, for example, when a subject is exposed to a visual field that rolls at a constant velocity of 30°/s about a horizontal axis, he feels himself both continuously rolling in the opposite direction at 30°/s, but only tilted by a constant angle of perhaps 10° to 15°. Clearly, visually induced roll alone is not sufficient to produce sustained roll rates without either other cues or the benefit of suggestion from the experienced pilot's active participation. If the roll or pitch is performed about a vertical axis, however, it will normally produce continuing and nonparadoxical visually induced rotation sensations.

Linearvection — Linear translation of an aircraft through a wide visual field also leads to visually induced motion effects (linearvection), although high-speed movement appears to saturate the perception of velocity. The sensation of horizontal or vertical motion can be generated on the basis of side-window displays alone or in junction with front-window or top displays. It is not necessary that the entire visual field be filled, but merely that a substantial part of the peripheral visual field be uniformly moving. High detail in the visual peripheral field may or may not be important for the generation of linearvection (Berthoz et al., Ref. 30).

Asymmetries in visually induced pitch and roll — For reasons that are not yet entirely clear, visually induced pitch down is easier to produce than visually induced pitch up (Young and Oman, Ref. 31). When the entire forward visual field pitches downward in accordance with a pitch up motion, the motion sensation experienced frequently consists of a combination of pitch up and upward linear motion. Asymmetry is frequently observed in visually induced roll, with any individual subject having greater sensitivity to a preferred side. Although these asymmetries may be rather large, they are not yet fully understood. They may or may not be related to asymmetries in sensitivity of the vestibular apparatus to tilt in either direction.

Effectiveness of upper and lower visual fields — Stimulation of the lower visual field is particularly effective in producing sensations of forward linear motion, whereas stimulation of the upper visual field appears to be more relevant to production of sensation of pitch. Depending on the maneuvers being used in a given flight simulation, more or less attention should therefore be devoted to provision of moving contours in the lower or upper visual field (Young and Oman, Ref. 31).

3.2.3 Interaction between platform motion and wide-field visual stimulation

Visually induced motion cues can provide an extremely effective way of producing the illusion of sustained linear or angular velocity in a flight simulator. Although visually induced motion sensation may saturate at high linear or angular speeds in a simulator, this is also true in the actual aircraft and, consequently, does not imply underlying physiological or psychophysical limitation on its use. The principal limitation of exclusive reliance on visually induced motion in flight simulation is the situation of rapid changes in linear or angular velocity. When sudden changes in visual field velocity are not accompanied by confirming platform motion or tactile cues, there can occur a disturbing and often lengthy time delay in the development of self-motion. During this period of time, the visual field may appear to move, while the pilot and his surrounding cockpit are perceived to remain stationary. On the other hand, the presence of compelling visual stimuli probably decreases the requirements for motion stimuli. Merely a slight platform displacement or seat motion in the appropriate direction may be sufficient to bring forth well-developed vection.

In the absence of confirming motion cues, such as might be generated by platform motion, there are constraints on the magnitude of visually induced motion effects as well as on onset times. When the head is in other than the erect position, the limitations of the gravitational cues on visually induced motion are reduced, and the visual effect is seen to be predominant, especially with the head on the side or in an inverted position. The relevance of this to the realistic flight training simulation situation, however, is limited at best.

3.2.4 Ordering of sensory cues

The normal ordering of sensory cues according to their dynamic response appears to be the following:

- Tactile cues respond most rapidly to changes in pressure, and signal any rapid changes in acceleration because of the consequent change in support force. They are the ideal first simulator cue for rapid onset.

- Vestibular cues, both semicircular canal and otolith, are also responsive to accelerations and, to a limited extent, to linear and angular velocities. Their stimulation, through appropriate platform motion, is consequently of principal interest for demonstrating and simulating sudden changes in linear or angular velocity, over periods from hundreds of millisec to the order of 10 sec. They are particularly important when early detection of aircraft acceleration is required to avoid instability or to react to critical failures.

- Visual cues concerning attitude or rate are most important for accurate alignment and for steady, slowly changing velocity perception. Moving visual scenes are especially appropriate for low-frequency motion simulation with quasi-steady-state velocity segments extending over a time of more than 10 sec.

When conflicts arise between sensory information coming from the different sensory modalities, they are frequently resolved in favor of the shorter time-constant sensor, at least initially. For example, visually induced motion, when suddenly put in conflict with oppositely directed platform motion, will dramatically disappear and only slowly reappear over a period of many seconds while platform motion cues

dominate. It is therefore essential that wash-out schemes avoid the generation of significant visual-vestibular conflicts. Of particular importance is the avoidance of situations in which there is a direction difference between the visual and vestibular cue mechanisms.

3.3 Conclusions and Recommendations — Physiology

Technical limitations on both motion systems and visual systems necessitate compromises with objective fidelity. Careful consideration of the dynamic characteristics and thresholds of the human motion sensors and the visual system is required to determine the simulator specifications for achieving perceptual fidelity in a given aircraft and maneuver. It is recommended that in simulator design, emphasis be placed on obtaining perceptual fidelity rather than objective fidelity.

The state of knowledge of sensory information is not sufficient to completely define the needs for simulation. Some of the material not readily available may exist in the perception literature in forms which could be made useful to the simulator community. In the visual display area, for example, the considerable literature on the relationship between visual acuity and display size, contrast, brightness, orientation, position in the visual field, velocity, and color could be brought to bear on requirements for adequate visual displays. In the vestibular field, the models for dynamic processing of combined linear and angular acceleration cues in terms of perceived orientation could be brought to bear on the design of more efficient motion platform algorithms. It is also clear that there are a number of areas covering important characteristics of the physiological sensors in which information to answer the needs of the simulator designer apparently does not currently exist. A thorough study of these gaps in the literature as well as the aforementioned collection of existing literature is of utmost importance in supporting research in simulator technology. Table 1, drawn from a preliminary working document prepared by Boeing for a contract on integrated cuing requirements being carried out for the USAF Human Resources Laboratory, lists many of the more important areas of perceptual cues which should be documented in a manner that will be useful to simulator designers.

Future research activity in the area of visual and motion cues should be directed toward applications that bear direct relationship to the cockpit simulation environment and not be limited to the traditional, simpler, laboratory experiments of the perception psychologists.

Recommendations

1. In the design of simulators, emphasis should be placed on perceptual fidelity rather than objective fidelity.

2. Research is required to tailor platform motion algorithms to match human dynamic processing of combined linear and angular acceleration.

3. Research is required in determination of requirements for adequate visual displays.

4. Further development is required for mathematical models of spatial orientation including tactile cues.

TABLE 1: Preliminary data-base control requirements.

USER-ORIENTED CHARACTERISTICS

Visual Ability
- Modulation Sensitivity
- Scene Effects
- Temporal Effects

Auditory Ability
- Tone Discrimination
- Thresholds
- Masking
- Fatigue
- Temporal Effects
- Sound Localization
- Speech Intelligibility

Vestibular Ability
- Thresholds
- Orientation Thresholds
- Acceleration Thresholds
- Eye Control
- Muscle Control

Somesthetic Ability
- Cutaneous Threshold
- Adaptation
- Kinesthetic Cues
- Temperature Sensitivity

Olfaction
- Threshold

Motor
- Muscular Feedback
- Resistance Thresholds

Depth Perception
- Monocular Cues
- Binocular Cues
- Individual Differences
- Learning

Perception of Size and Distance
- Effect of Visual Angle
- Size Constancy
- Distance Constancy
- Interactions
- Individual Differences
- Learning

Cross-Modality Interactions

Perceived Orientation in Space
- Visual Cues
- Vestibular Cues
- Auditory Cues
- Perception of Position
- Perception of Orientation
- Perception of Slant
- Perception of Motion
- Induced Motion
- Individual Differences
- Learning

DISPLAY-ORIENTED CHARACTERISTICS

Visual Image
- Level of Detail
- Accuracy
- Geometry
- Shading, Texture
- Superposition
- Defects (Staircasing, etc.)
- Inserts
- Depth of Field

Visual Display
- Collimation
- Distortion
- Resolution/Contrast
- Phosphor Persistence
- Luminance
- Color
- Defects
- Transport Delay

Visual Display (cont.)
- Update
- Field of View
- Match to Adjacent Display

Auditory Display
- Transport Delay
- Spectral Fidelity
- Intensity
- Ambient Masking

Motion Base
- Transport Delay
- Degrees of Freedom
- Acceleration Capability
- Smoothness
- Motion Range
- Washout

4. SIMULATOR TECHNOLOGY

This section provides an assessment of existing simulation technology. Those characteristics that could be expected to provide high perceptual fidelity are defined, and an attempt is made to show where current limitations exist.

The section is divided into three parts: a discussion of visual system technology, a discussion of motion system technology, and a review of fidelity considerations in crew stations and computer models. The sections on visual and motion systems are supplemented by appendices: Appendix B presents some data collected by the working group that defines the characteristics of a range of training simulator facilities. Appendix C provides a synopsis of pilot opinions of training simulators, and Appendix D provides a more detailed discussion of visual system technology.

4.1 Technology of Visual Systems

4.1.1 Introduction

It is taken as axiomatic that whenever a training task requires the perception of a feature of the world external to the aircraft, then some form of visual system displaying the feature will be required in the training simulator. While physical fidelity between the real world feature and the displayed image may not be required, and is in general unachievable, nevertheless certain characteristics of the image, in terms of physiological stimuli, can be identified and will assume varying levels of importance depending on the task being performed.

Appendix D contains a list of the factors that need to be considered in specifying a visual system. An attempt is made to identify levels of these factors which, if achieved, would provide physical fidelity so close to perfection as to satisfy the most exacting demands of the trainers. No visual system currently available even approaches this level of fidelity, nor, in general, is it necessarily important, for the training process to proceed, that it should do so.

Often the precise characteristics of the visual system are poorly defined. Accordingly, the Flight Mechanics Panel of AGARD has set up a Working Group to define the method of measurement of the characteristics of flight simulator visual systems and will publish its results in 1981.

4.1.2 Current systems

The visual display is composed of two major elements:

a. The data base

b. The viewed display

These may be subdivided as follows:

a. The data base:

   1) Physical models

   2) Computer stored

   3) Record of the real world

b. The viewed display:

   1) Electronic video presentation

   2) Direct optical viewing

The systems may be further analyzed as:

a1) + b1) Modelboard plus TV camera and TV monitor or projector.
Modelboards plus laser camera and laser projector.

a1) + b2) "Point" light sources shining through transparent models, the "shadowgraph."

a2) + b1) Computer Generated Imagery (CGI) presented on a TV monitor or by a TV projector or by a laser projector.

a2) + b2) Not available.

a3) + b1) Film systems read by flying spot scanner and presented on a TV monitor or by a projector.

a3) + b2) Film systems projected by a film projector or a photographic transparency associated with a point light source.

The systems which are currently available and most widely used are the first three.

4.1.3 Limiting factors

Appendix D contains a detailed analysis of where the various elements of the visual systems fail to meet the ideal performance and identifies under what circumstances this failure may be important, or, in other words, when the training effectiveness may be degraded by a deficiency in the visual scene. While

all factors may be important at some time or another, this section will review only a very limited selection of deficiencies, emphasizing those considered to be more generally important and for which an improvement in the technology, at *reasonable cost*, might produce highly beneficial results.

Data base — Neither film-based systems nor shadowgraphs appear to offer much hope for improvement, and their application will be confined to special, and limited, applications. Laser light sources may provide adequate operating area for near-hover training for V/STOL aircraft; otherwise sky/ground projectors for high-altitude air combat are the main application. Film-based systems can be used only in applications where small deviations from the flight path are encountered.

Modelboards are able to provide high detail, but in order to provide adequate operating area with reasonable size, they need to be of small scale, which limits the minimum altitude. Depth of field limitations promise to be improved by the use of laser cameras. Consequently, these may allow somewhat smaller scales, though mechanical interference between the structure surrounding the entrance pupil and the model will still be a restriction. Where high detail is required, modelboards currently offer the only available technique; this is likely to be so for only a short time longer, and there is unlikely to be much further development of modelboards.

CGI data bases lack only detail content, but they are advancing rapidly. An increased content of edges and the creation of realistic texture, together with improved computation techniques and rates, offer the prospect that within a decade or so all the picture content needed for training will be available and that it will be updated at an acceptable rate.

Display devices — Field of view and resolution are of primary significance. For one channel and a given bandwidth, they are inversely related. The nominal 3 min arc resolution per pixel, on a 60° diagonal field of 1000 line TV display, is unlikely to be significantly improved. Even this resolution leads to practical realized resolution at least twice as poor. The best prospect for improved resolution over a large field of view is offered by the development of the laser projector. These projectors may be associated with either modelboard or CGI data bases. However, collimation of the laser projector display has not been achieved and is likely to be rather difficult.

An alternative to the conventional TV raster format is the calligraphic display, generally combined with rolling raster insertions for specific features, e.g., runway markings, horizon glow, etc. The resolution of these displays is at least as good as, and generally better than, conventional TV, though they also generally have a limited color spectrum, using a penetron tube. However, a full color calligraphic projector has been demonstrated, and it is expected that several of them can be combined to give a wide-angle, collimated, field.

4.1.4 Interactions between and within devices

In many cases, the factors characterizing the visual system are not mutually exclusive, either in the ease with which they can be generated or in their contribution to the training process. For example, levels of contrast, brightness, and color can be interchanged while maintaining a given level of visual system complexity. Appendix D gives some indication of the tasks in which the various visual system factors may be important. This should provide a basis for judgment on where future development effort should be expended.

In addition to interactions between visual system characteristics, there is a powerful interaction between visual and motion cues. Generally, this is in the realm of motor skills, and it is evident that a large field of view can compensate to some degree for limitation in, or absence of, a motion system in those cases where lead cues are needed for proper control. Whether it is sensible to provide a large field of view for this purpose, when it is not otherwise required for the training task, rather than a motion system, needs to be considered on cost-effectiveness grounds.

4.1.5 Future developments

There is little doubt that the source of visual image generation information will in the future reside in computer systems, and that continuing effort will result in high-fidelity scenes. The cost of computer hardware for a given capability continues to reduce, although the demand for more keeps costs up, and the techniques of utilization continue to improve. The major requirement is for better techniques for the generation of the data base, so that when the complexity predicted becomes available for display, excessive costs are not involved in creating the complete system.

The main thrust in the development of image presentation devices is less clear, though it is probably the most important element in the system. A current prospect for presenting high-resolution, large field-of-view scenes is the laser projector. However, alternative systems, based for example on area-of-interest helmet mounted, solid-state panel, or holographic techniques, need to be pursued. Any one of several visual technologies could eventually meet requirements, and the front-runner is expected to shift many times in the future as the cost and performance pendulum swings with technological advances.

4.1.6 Research requirements for visual technology

The accurate reproduction of the information content of the real world in all its facets, by a simulator visual system, is not within sight of realization. The most valuable contribution toward easing the task of providing an acceptable approximation to the true scene would be the identification of those elements of the visual scene which are important for training in a variety of identifiable tasks. This, too, seems to be practically impossible at present. A realistic approach, therefore, is to identify the major components of the visual scene and endeavor to concentrate on those features which should be capable of improvement.

Data base — This technology can be divided in two broad categories: techniques based on a physical analog of the real world (e.g., modelboards, shadowgraphs, and film systems) and techniques based on computer models.

Of the physical analog systems, the film technique does not appear to be very promising. The limited operating envelope and the inaccuracies introduced by the distortion of the image render them unsuitable for general application. Avoiding these deficiencies requires the generation of a film base containing all possible viewpoints within a specified operating envelope and the development of a technique for selecting and displaying the appropriate viewpoint. The generation of the film base might be possible, but it would be immensely costly; there is no known method of selecting and displaying the appropriate viewpoint.

The shadowgraph is in the same category as the modelboard, with the added restriction that the size of the model is more severely limited. A long-term possibility is the viewing of a directly projected hologram, where the holographic plate is constructed of a multitude of separate holographs, sequentially assembled. The cost would be very high. Consequently, shadowgraphs are likely to remain of value only for special applications, such as the current sky/ground projectors, and possibly for generation of a large field of view for V/STOL operations in and around hover. Here a brighter, smaller, light source would be of value, and utilization of lasers offers possibilities. Nevertheless, diffraction limiting will imply resolutions of about 10 min arc at best.

Modelboards can contain high detail but have fundamental limitations on operating volume. Scale is determined by minimum height, which in turn is controlled by the bulk of the optical probe and by the depth of field achievable. The laser camera may provide adequate depth of field by dynamic focusing, but there is an inevitable limitation on the location of the entrance pupil due to mounting structure. This structure is even more embarrassing in TV camera systems if combined with a requirement for a large field of view, due to the bulk of the optical probe. Consequently, several modelboards are required to cover a reasonable operating volume, thus occupying a lot of space and incurring high running costs. There is no obvious means of improving the modelboard by a technical innovation, though the introduction of a laser camera system, with its better resolution, will make heavier demands on modeling skill than in the past. Modelboards still offer the richest scene content.

CGI data bases have only one major defect — lack of data content. Rapid advances are being made. Continued emphasis on the creation of realistic texture to reduce the demand for edges is indicated. At the same time, increased edge content is needed, with particular emphasis on the selection of the edges to be displayed so that invisible (from the current viewpoint) edges are not computed. Saving of edge numbers by the direct generation of curved edges (initially essentially ellipsoidal) is under development. The detail that can be generated for a given computing speed is largely a function of the allowable transport lag. Continual improvement in computing speed, increased use of parallel processing, and improvement in computing algorithms all offer possibilities for more realistic scenes.

Display devices — Field of view and resolution appear to be the overriding factors, and are interrelated. The bandwidth of the system determines the resolution per unit steradian. While such features as brightness, contrast, and color are all important, they appear to be less limiting than the first two factors. The laser projector appears to offer significant improvements over current systems in both field of view and resolution, primarily by virtue of its 100 MHz bandwidth. Considerable, probably expensive, development will be required to obtain a collimated display, but projection onto a screen of 2 m or more radius would overcome one of the major objections to lack of collimation, that is, the 2 m eye-screen distance would require the pilot to change focus when transferring from head down to head up, or vice versa.

The most common form of display device is the television monitor. It is limited to about 3 min arc resolution on a 60° diagonal display field (this is reduced in practice to 8-10 min arc to avoid aliasing). There is unlikely to be a significant improvement. Multiple monitors, each subtending a smaller angle and simultaneously providing a larger field of view have not been favored, partly because of cost, but also because of the difficulties of collimation, and of merging the images.

There is an urgent need for improved display devices to take advantage of hoped-for improvements in CGI data bases. A number of techniques are under development; for example, matrices of LED or LCD and liquid crystal light valve projectors. An example of the latter is under development, and it may achieve 1 min arc over a small field and perhaps 4 min arc over a large field. This exceeds the present capability of laser projectors. Another device under development is the head-mounted display, where a limited instantaneous field of view, with concomitant high resolution, can be observed anywhere over a much larger field.

Conclusion

There is every possibility that continued development of CGI along the present lines will produce in the data base a scene with adequate content for the training role. The more pressing need would appear to be the development of a display device capable of making full use of this potential.

4.2 Technology of Motion Systems

4.2.1 Introduction

In describing equipment it is desirable to express capabilities in terms relevant to the intended use, in this case, cockpit motion in aircraft simulation for training. However, it is impractical to attempt to describe a motion system's capabilities in terms of training maneuvers or objectives, since there exists no obvious and accepted measure of motion cue requirement. The current practice is to simply list the motion equipment's performance capabilities in terms of degrees of freedom and their individual maximum accelerations, velocities, and excursion amplitudes. An attempt to promote systematic and complete physical descriptions of motion systems is seen in the work of AGARD FMP Working Group 07 in their report

"Dynamic Characteristics of Flight Simulator Motion Systems" (Ref. 11), but they avoided any attempt to relate their measures to pilot cuing capabilities.

Published descriptions of motion equipment capabilities are mostly limited to R&D systems and manufacturer's developmental models. The literature in this area is well covered by Puig, Harris, and Ricard (Ref. 17). However, very little information is available on actual motion performance as utilized in day-to-day training systems after the acquisition acceptance testing is completed. Differences from the original manufacture standards can result from individual user tailoring performance based on his available expert sources, usually subjective, in an effort to optimize performance for his training purposes. Also, over the life of the equipment, maintenance and calibration procedures may change as well as safety requirements. With the above comments in mind an attempt was made to obtain representative trainer motion system characteristics. It was found that such data are not uniformly available across trainers and, with no reference or standard, it is difficult to make judgments or draw conclusions concerning the fidelity of motion characteristics.

Recommended standards and tolerances for acquisition of motion systems for trainers are about the only available quantitative reference to judge motion performance. Harris (Ref. 32) prepared a summary table of U.S. Military Standards for motion hardware and added recommended tolerances based on his work. The AGARD Working Group 07 report contains data comparing older generation motion platforms and the post-1975 generation with hydrostatic bearing. These data show that major improvements have been made in hardware performance. This is especially true in the critical areas of acceleration noise and time lags. Older generation platforms often did not meet the recommended tolerances, whereas the new systems appear to meet or exceed levels of these critical areas. Newer generation motion platforms, if combined with improved drive algorithms, faster computation rates, and better aircraft data, will lead to better motion-system performance. Whether this will be sufficient to be of benefit to training is unknown, since there is no reference as to how much is required for effective training and no training transfer data have been reported from the newer systems. When transfer of training tests are run in the future, the data will not be generalizable beyond the notion of "motion on" or "motion off" unless the characteristics of the motion system are documented in detail. This documentation must include the physical characteristics of the hardware as described in the WG-07 report and details regarding the drive (or "washout") logic.

4.2.2 Motion equipment capabilities

AGARD FMP Working Group 07 recommended that the five characteristics listed below be used to describe the dynamic capabilities of simulator motion platforms:

1. Excursion limits, distinguishing between system limits and operational limits.

2. Describing function.

3. Linearity and acceleration noise.

4. Hysteresis.

5. Dynamic threshold.

The characteristics with complete definitions and test methods are given in Ref. 11. Two familiar and usually available characteristics are the system excursion limits for each degree of freedom (DOF) and the describing function or Bode plot. Examples of excursion limits can be seen in the data collected in Appendix B. However, the motion cue capabilities of the equipment is probably best represented by two characteristics called the operational excursion limits for sinusoidal input signals and the dynamic threshold. The first of these two factors determines the motion cue magnitude the platform can provide without generating unacceptable acceleration noise (defined as the perturbations of the output acceleration from its nominal 0.5 Hz sinusoidal value in the case of a 0.5 Hz input). The second determines how quickly it can provide the cue (i.e., the time lag between the acceleration command and achieving a response of 63% of the command). These two important characteristics are not reported for any current trainer motion platforms but have been measured on some R&D units. Recent improvements in new motion platforms have come about through the use of hydrostatic bearings and improved servo-valves which reduce acceleration noise (increases operational excursion limits) and which reduce dynamic threshold (cut time lag). Figures 5 and 6 give examples of these characteristics for platforms with and without these improvements.

The concept of operational excursion limits is illustrated in Fig. 7. In a conventional plot of log velocity vs. log frequency, the system limits of displacement, velocity, and acceleration are given by straight lines. Within this theoretical operational area other lines are given for constant noise ratio, which is the ratio of the standard deviations of the output acceleration noise to the nominal sinusoidal output. The crosshatched area represents the dynamic operational space usable without exceeding that noise level. This description is for single degree-of-freedom operation. In the case of a synergistic motion system, all degrees of freedom interact and use up part of the space of every other degree of freedom since they share the same hydraulic actuators.

Modern motion platform capabilities can eliminate many prior complaints. Acceleration noise, including turn-around bump, can be reduced well below 0.04 g. Platform response has been improved so that acceleration cue delays are now in the 50 millisecond range. This will significantly improve response, smoothness, and operation excursion limits. However, due to trainer facility space limitations it is anticipated that system excursion limits will not be increased, and therefore, no significant increase in motion cue magnitude or duration will be made. The main effect will be to clean up and actually realize the capability that should have been but was not obtained from older units.

Because of limited amplitudes, particularly in the translational degrees of freedom, other techniques for cuing acceleration have sometimes been employed. The pressure, proprioceptive, or kinesthetic senses have been stimulated by devices such as g-suits, g-seats, and helmet or arm loaders. Experiments have

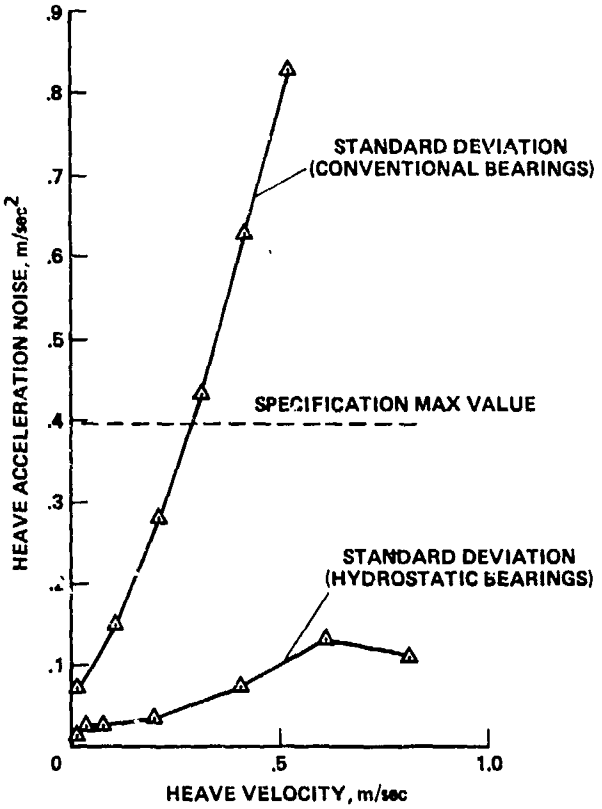

Fig. 5 Acceleration noise comparison for 0.5 Hz sinusoidal heave excitation

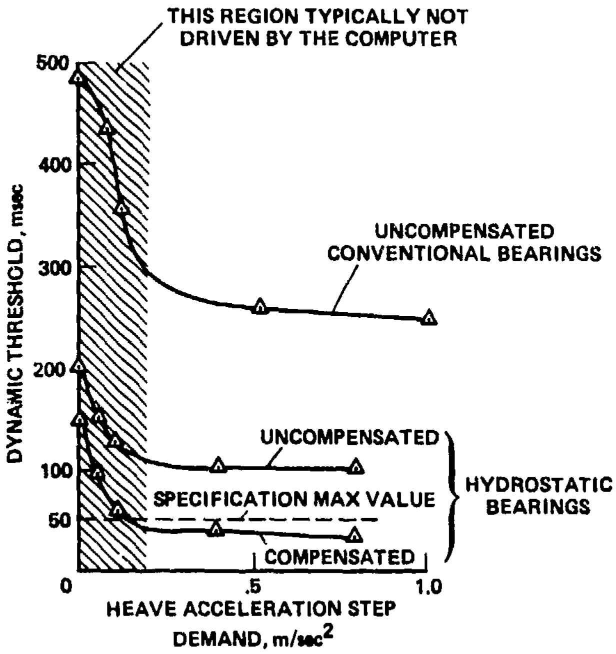

Fig. 6 Dynamic threshold comparison

disclosed modest subjective and performance benefits in some applications of these "substitute" cues, especially in simulation of high-g combat maneuvering, but their value in the context of training has not been established.

4.2.3 Motion cue response

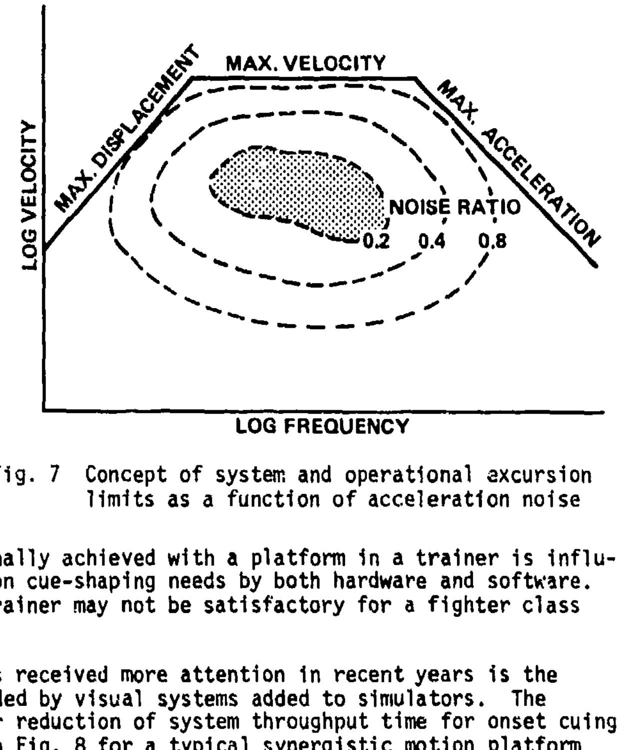

Fig. 7 Concept of system and operational excursion limits as a function of acceleration noise

Probably more important than the acceleration cue amplitude or its duration is the timing of its arrival to the pilot. It should be close to that experienced in the aircraft, and certainly in advance of visual position and velocity cues, if it is to perform its function of providing lead information to the pilot. A motion platform is used to provide sustained acceleration cues through platform tilting (sometimes called gravity align) which requires only a slow response. It is also used to provide acceleration onset cuing which can require very fast response especially in the roll axis. A hydraulic motion platform is a powerful device and can have very fast response especially with the new hydrostatic bearings and improved valves. The response finally achieved with a platform in a trainer is influenced by safety, acceleration washout, and acceleration cue-shaping needs by both hardware and software. Tradeoffs made in these areas for a transport-class trainer may not be satisfactory for a fighter class trainer.

An area of improved motion cue response which has received more attention in recent years is the increased computer update rates which have been demanded by visual systems added to simulators. The doubling of computer update rates can produce a bigger reduction of system throughput time for onset cuing than doubling the platform response. This is shown in Fig. 8 for a typical synergistic motion platform responding to a pilot's step input. The computer update rates of 15 and 30 Hz are representative of older and more modern trainers, respectively. The doubled update rate cuts 50 milliseconds from the throughput time, while doubling the platform response cuts only 33 milliseconds. The cost of the added computer capacity in today's market is likely to be less than the impact due to motion platform hardware and software changes to double response. The important part of the above discussion is that computer throughput time may be a greater contributor to motion cue lag than the platform response itself and must be considered when reviewing a motion system's capabilities.

4.2.4 Motion system drive laws, or "washout"

A necessary step in relating a motion system's excursion, rate, and acceleration capabilities to its cue-producing potential in various simulated flight situations is a consideration of the logic used to

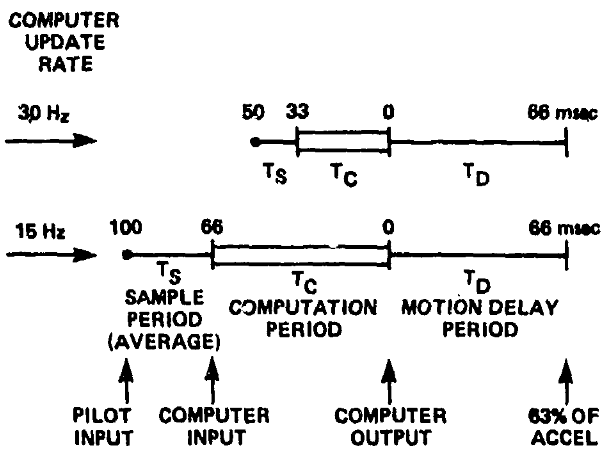

Fig. 8 Effect of computer update rate on motion cue lag after pilot input

attenuate the motions of flight to the excursion envelope of the simulator. While more complex schemes exist, the commonly used techniques of linear high-pass filtering and direct attenuation are suitable for the following discussion, which is intended as a brief illustration of a process that must be carried out when defining the drive laws of a motion system.

In the most general sense, the linear motions of the cockpit in space must be attenuated for the simulator, both directly and by passing the accelerations of flight (Earth-referenced vertical, lateral, and longitudinal accelerations) through high-pass filters of at least second-order. The characteristic frequency of each filter is directly related to the maximum amplitude of the lower frequency accelerations anticipated in the flight to be simulated, the excursion envelope of the motion system, and the degree to which direct attenuation is acceptable or necessary. If, for example, the motion system has ±2 ft of excursion allotted for vertical motion, and low-frequency incremental vertical accelerations of greater than ±0.5 g are seldom seen in the simulated flight task, a suitable "wash-out" filter characteristic frequency is about 3.0 rad/sec if direct attenuation is not used. An examination of the Bode diagram of Fig. 9 discloses that with this filter the simulator can produce reasonable facsimiles of flight acceleration only at frequencies above 6 rad/sec (1 Hz). Also indicated is the fact that input motions at frequencies near the characteristic frequency are passed on at significant gain but with grossly distorted phasing. If the simulation is that of a fighter aircraft maneuvering with accelerations of 8 g or more, the filter characteristic frequency must be of the order of 10 rad/sec. On the other hand, in the low-g maneuvering seen in some helicopter simulations, filter frequencies as low as 1.5 rad/sec might be feasible. Thus, it is seen that ±2 ft of vertical motion affords extremely limited opportunities to represent vertical motion cues in the important range of maneuvering frequencies (roughly 0.5 to 10 rad/sec), but in all cases it retains a capability for representation of the alerting or physiologically stressing higher-frequency motions that are also important to perceptual fidelity. For a given aircraft acceleration envelope, the excursion requirements of the motion system vary inversely with the square of the washout filter frequency. Hence, provision of more of the maneuvering frequency range of maneuvering vertical accelerations is an expensive undertaking.

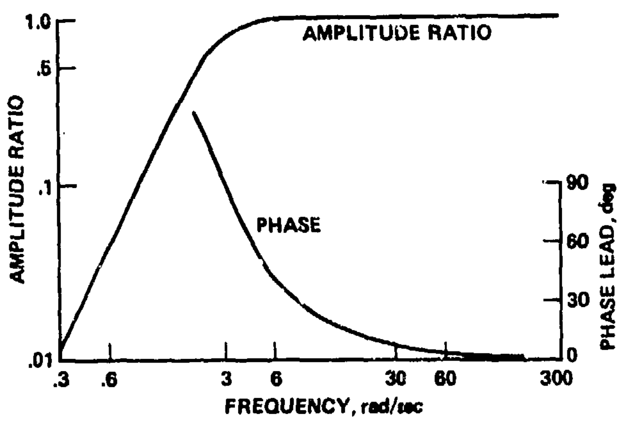

Fig. 9 Characteristics of a second-order "washout" filter with a characteristic frequency of 3 rad/sec

Rotational accelerations of flight must suffer, to some degree, a similar attenuation procedure, but the considerations regarding direct attenuation and/or filtering are more complex. Pitch and yaw accelerations need minimal constraint, especially in simulations of transport or cargo category aircraft. Special attention must be given to the representation of roll accelerations because of the following factors: 1) unacceptability of false lateral accelerations sensed at large simulator tilt angles, and 2) the unacceptability of washout filter frequencies (second order) above about 0.7 rad/sec in the rotational modes because of the resultant disorienting phase differences in the motion cues relative to the visual cues. Thus, it is necessary to directly and grossly attenuate rolling accelerations, particularly of small combat aircraft. Unfortunately, experience has indicated that attenuations of either angular or linear accelerations to less than about 0.4 of their real values seriously degrade the effectiveness of the cue.

These examples have been cited in part to illustrate the severe inherent constraint on objective fidelity of simulated cockpit motion in simulations of highly maneuverable combat aircraft. However, in the simulation of the many important piloting tasks involving much lower acceleration amplitudes (large aircraft, helicopters), a significantly greater fraction of the aircraft's maneuvering frequency spectrum can be reproduced. An example of relating simulator motion system capabilities to the maneuver envelope of an aircraft is seen in Ref. 33, which includes a description of the development of specifications for a motion system to be used in helicopter research.

Attributed to Gundry (Ref. 34), and discussed further by Caro (Ref. 35), is the concept of differentiating between "maneuver" motion cues and "disturbance" motion cues and optimizing motion system requirements for the hopefully smaller excursions represented by the latter category. It can be argued that practical differentiation between the two categories of cues must be on the basis of frequency content. Cues such as stall buffet, or the various "bumps" associated with the operation of an aircraft, do not intrude down into the maneuvering frequency range cited earlier. However, motions from disturbances such as atmospheric turbulence or asymmetric engine failure do have significant maneuvering frequency content and must be countered by pilot input at these frequencies. In this latter case, presenting the disturbance motion cues without the corresponding cues resulting from the pilots' response appears neither practical nor desirable.

4.2.5 Research requirements for motion system technology

The limiting characteristics of motion platforms can be reduced to two fundamental features -- the limited movement envelope and the fidelity with which the movement takes place within that envelope. Unless the movement envelope is driven to larger excursions by an as yet unidentified requirement, it is assumed that improved platform hardware can now meet known dynamic specifications. Only the software and drive philosophy remain as having potential for changing the role of motion platforms from training effectiveness noncontributor to contributor.

It is recommended that a research program be conducted jointly by designers and training methods personnel. The first objective would be to develop motion drive software. These drive models would then be used with new generation motion platforms in transfer of training experiments. With appropriate highly dynamic tasks and lower stability aircraft (both fixed-wing and helicopters), as well as with and without visual systems, it should be possible to determine if there is a real training role for motion platforms in simulators.

It is further recommended that new technology R&D efforts be encouraged in the area of inside-the-cockpit motion cuing devices for both fixed-wing and helicopter flight trainers. If an effective training motion cue role can be established, it would be more cost effective to have it fulfilled by devices such as g-suits, body and helmet loaders, seat shakers, and other inside-the-cockpit devices.

4.3 Fidelity of the Crew Station and Computer Model

4.3.1 Introduction

It is the purpose of this subsection of the report to review the remaining components of simulation with regard to their potential influences on the fidelity of the simulation. These components are the crew station itself and the mathematical model in the computer that is intended to reproduce the responses of the aircraft to control inputs and environmental perturbations. The primary elements of cockpit equipment and the computer model are listed. The significance of fidelity in each of these elements is discussed, and the topic is concluded with some observations on the temptation to compromise objective fidelity to obtain perceptual fidelity.

4.3.2 Cockpit and computer model components

Cockpit equipment — When one considers the physical attributes of an airline training simulator, or any of the modern simulators related to particular military aircraft, the question of cockpit fidelity seems academic. It would appear that the great bulk of the hardware fully duplicates that of the aircraft. In fact, much of it is acquired from the aircraft manufacturer. However, the newer "generic" general aviation simulators, or the various levels of transport aircraft "procedures trainers," demonstrate that widely diverse levels of equipment fidelity are appropriate within the full range of the flight training objectives. Thus, as a basis for further discussion, the following list of simulator cockpit components is offered. The fidelity of some of these components is measured not only by their dimensions and appearance, but also by their dynamic response characteristics, that is, their capability to respond faithfully to the signals from the simulator computer or to the inputs of the pilot. Examples of poor equipment dynamic fidelity might be unrealistically large hysteresis in an attitude indicator or incorrect friction in thrust controller actuation.

I. Enclosure, panels and consoles

II. Seats and constraints

III. Controllers

  A. Flight controls

    1. Center stick, column, side stick, collective

    2. Pedals (yaw control, brakes)

    3. Thrust controllers

    4. Configuration controllers (flaps, gear, etc.)

  B. Systems controls (switches, knobs, keyboard, etc.)

    1. Automatics (SCAS, autopilot, etc.)

    2. Weapons

    3. Navigation

    4. Communication

    5. Aircraft management (fuel, electrical, etc.)

IV. Displays

  A. Flight instruments

    1. Attitude

    2. Speed

3. Navigation

4. Engine parameters

B. Electronic displays

1. Head-up display

2. Radar, FLIR

3. EADI — EHSI

C. Annunciations

1. Warning lights

2. Navigation modes

3. Weapons status

Mathematical model — The simulator computer contains definitions of the performance and the dynamic response of the simulated aircraft and its systems. The following list of typical computer program elements will be addressed in a discussion of existing limits on objective fidelity. While the modeling of a digital stability augmentation system may be easily assessed as valid because it is in fact a reproduction of the flight system, fidelity of the simulated aircraft's response to control surface deflections or its environment is not easily attained and verified.

I. Aircraft dynamics

A. Basic equations of motion that define the motions of the aircraft in accordance with the forces exerted upon it and its mass characteristics

B. Mass properties — geometry, weight, center-of-gravity, and moments of inertia as they are affected by loading, external stores, etc.

C. Force "build-up" equations, the definition and summary of all of the force and moment components to be considered in each of the six degrees-of-freedom of motion

D. Forces and moments

1. Aerodynamic forces and moments as they vary with dynamic pressure, incidence angles, control surface deflections, configuration changes, rotational and incidence angle rates, Mach number, airframe flexibility, proximity of the ground plane, engine operating conditions, etc.

2. Landing-gear forces, as defined by gear geometry, spring and damping characteristics, and tire-surface friction for a variety of surfaces

3. Propulsive forces, as defined by the propulsion system model

II. Structural dynamics — In rare cases, limited simulation of structural modes may be appropriate if the frequencies are low enough to interfere with pilot control.

III. Propulsion system

A. Forces — net force and torques on the airframe as defined by engine specifications and conditions of altitude, temperature, and Mach number

B. Dynamics — the time response of the propulsion system to control inputs

IV. Flight control systems

A. Controller forces and displacements — defined in various ways, depending on the nature of the control system, but always including the dynamic effects of mass and friction

B. Control system logic — the modeling of the control surface response to controller signals, measures of aircraft state, and actuator system dynamics — and including representation of the limitations in sensing of aircraft state

C. Automatic systems — mechanization of automatic flight control modes, e.g., autopilot, autothrottle, automatic intercept and tracking, etc.

V. Navigation systems

A. Ground based systems — VOR, TACAN, ILS, beacons, etc.; functional models plus library of stations

B. Onboard systems — INS, radar, FLIR, etc.

VI. Weapons systems

A. Firing-launch-release logic

B. Modeling of weapons trajectory for effectiveness evaluation

C. Unique threat-warning systems

VII. Display dynamics

A. Flight director computations — modes and logic

B. CRT displays, panel or head up — symbol generation and display logic

VIII. Environment

A. Atmospheric statics — ranges of variations in temperature, pressure, and density with altitude

B. Atmospheric dynamics

1. Winds, including normal variation with altitude

2. Turbulence, to a level of sophistication suitable to the simulated flight task

3. Discrete large amplitude perturbations — shears and vertical drafts

C. Runway surface conditions; ice, standing water, dry, roughness

The remaining items, unlike those above, are not related directly to the description of a particular vehicle system, but to the computational system that is used to translate these descriptions into a dynamic representation of the vehicle.

IX. Computational dynamic fidelity

A. Computation interval — likely to be several to cover the range of high- and low-frequency components

B. Integration and filter algorithms

C. Input-output lags

X. Program language and executive routines — facilities for data extraction and model alteration

Cockpit noise and vibration — Vibration modeling and cuing might be considered part of motion simulation; however, along with cockpit noise it is related to the specific aircraft simulated and thus subject to the same type of fidelity assessment as cockpit equipment and the computer model.

I. Cockpit noise

A. Engine (and rotor or propeller)

B. Airstream

C. Configuration changes

D. Weapons

E. Alarms

II. Vibrations

A. Structural mode responses

B. Buffet — stall or Mach number

C. Rotor

D. Engine — engine failure

4.3.3 Current fidelity levels

The simulators most recently acquired by commercial airlines and the military reflect efforts to obtain high levels of objective fidelity in both cockpit equipment and in representation of the aircraft and its systems' dynamic performance. Certainly perceptual fidelity levels are recognized to be much higher than in the simulators of the 1960s, and not all of that progress can be credited to improved visual and motion systems. At least four additional factors can be credited for this improvement: 1) quantitative descriptions of the newer aircraft and their systems are much more extensive than those of earlier aircraft; 2) computer capability-to-cost ratios have increased tenfold; 3) hard experience has tended to define the important impediments to fidelity; and 4) it has been recognized that simulators deserve a level of maintenance similar to that of the airplane.

Thus, it has been demonstrated that strong objective fidelity can be obtained in most details of cockpit equipment and computer model, but history has also shown that inadequacies in a single small but important element of a simulation can seriously impair overall perceived fidelity of the system. The discussion that follows uses the previous lists as an outline to describe practically attainable objective fidelity and to point to areas where objective fidelity is particularly vital to perceived fidelity. This discussion addresses each element with the implied assumption that its presence is of primary significance to some particular training objective.

Cockpit equipment — I and II: The appearance and geometry of panels, consoles, and seats are usually made like the aircraft because the simplest design is to duplicate the airplane or, if the simulation is generic, a suitable airplane. In any event, it is important to have instruments, etc., in their correct location. If the number of simulators to be produced is small, it may be fiscally prudent to use actual aircraft hardware. The remainder of the cockpit enclosure is of less importance, since it has little functional significance other than to block out the view or to frame the visual simulation.

III: The primary flight controls are among the most sensitive elements in terms of fidelity requirements. The force-generating systems associated with the stick or column and pedals are seldom aircraft hardware, though fly-by-wire systems like that of the F-16 might typify exceptions. The newer hydrostatic-bearing hydraulic "control-loaders" have expensively demonstrated impressive capabilities to provide the forces defined by the computer model, but this fidelity can be easily compromised by inadequate maintenance coupled with poorly defined performance criteria and measurement. Simpler spring-damper-friction systems employing electric actuators for trim and gradient change functions are attractive for some applications. The only other controller element requiring special attention might be the thrust levers. Here again, the pilot demands smooth, precise actuation. Among the switch and button types of input devices, only those associated with the stick or wheel or thrust levers, or seldom-used emergency devices, deserve a high level of position and force fidelity. Most of the others might well be relatively inexpensive facsimiles, but with the same function and actuation sense.

At this point it is appropriate to make an observation based on several decades of experience with research-oriented flight simulators. The simulator pilot tends to be much more critical of nonlinear aberrations (friction, dead-bands, "slop," poor centering) in his primary maneuvering controllers in the simulator than in the airplane. In fact, it might be generally stated that specifications in these matters should be more demanding in the simulator than in the airplane. Sensitivities have been noted with regard to similar deficiencies in attitude or command displays, for example, the ADI elements. The following hypothesis is offered for this behavior:

Even in training simulators equipped with motion systems, the pilot is deprived of much of the flight spectrum of motion response to his control inputs, especially in the longitudinal control mode where maneuvering-frequency normal accelerations are essentially absent. The pilot is forced to compensate for this attenuation of feedback cues by exercising a more "precognitive" mode of control, that is, a mode in which more reliance is placed on a subconscious prediction of the initial response to his control input. Confirmation of this prediction is then perceived in the response of the instruments. This might be termed the "simulator pilot" mode. Erratic nonlinear controller or display dynamics that might be judged tolerable in the flight environment with its acceleration cues may seriously hinder the simulator control process that must be learned and practiced without them. In a later section dealing with the computer model, the basic theme of the above hypothesis is repeated in explaining other cases in which verified objective fidelity failed to result in perceptual fidelity.

IV.A: High fidelity reproductions of flight instruments have become the norm in flight simulators, and in some cases, notably the synchro-driven ADI and HSI, slightly modified flight hardware is commonly used. The primary threat to fidelity is inadequate inspection and maintenance.

IV.B: The various electronic display units in a simulator cockpit might well be from the same production line as flight equipment. In some applications, head-up display symbology might be generated within the CGI visual simulation itself, eliminating the need for a costly separate display unit with its attendant alignment requirements.

In summary, it can be stated that though the *static* objective fidelity of cockpit equipment is readily defined and effected, dynamic performance inadequacies in some elements may be the unrecognized source of reduction in overall perceptual fidelity of the simulation, as well as task performance difficulties.

Computer model of the aircraft and its environment — The past decade has seen a huge increase in the potential for objective fidelity in the computer modeling of aircraft performance and dynamic response. Application of computer technology in the design and testing of aircraft systems has resulted in complex high-quality descriptions that can be entered into the simulator computer. Because of the computer's vast capabilities, relatively little attempt is made to simplify the model; it is easier to put almost all available knowledge into the program than to define the simplifying approximations that would meet perceptual fidelity requirements. However, there are some secondary elements of the simulator computer model that are not routinely supplied with good descriptive data, and verification of fidelity in these areas can be difficult. Although termed secondary in the general sense, these elements might attain primary significance in certain training activities. Examples will be cited in the continuing discussions.

I.A: The rigorous equations of motion basic to flight mechanics' computations are readily available. Simplifications are seldom necessary or desirable, except perhaps the assumption of a flat, nonrotating Earth in the more basic applications.

I.B: Geometry and mass properties are usually described adequately in the engineering design data for the aircraft. Moments of inertia are the most critical items, since they are basic to the dynamic response of the simulated airplane, and they are difficult to verify.

I.C: The "force build-up" equations identify the individual force and moment components summarized for each of the six degrees-of-freedom of motion and thus define the level of complexity of the vehicle

dynamic model. However, they do not define the quality of the model; that definition rests with the quality of the information used in the computation of the individual forces and moments.

I.D: As indicated earlier, modern major aircraft development programs generally produce high-quality definitions of the aircraft's aerodynamic characteristics, derived from wind-tunnel tests and analysis. Those parameters associated with aircraft performance and dynamic stability and control tend to be of good fidelity because of their importance to the design process. These data generally become the backbone of the "simulator data" collection. Unfortunately, not all data are verified or updated after flight test, and many uncertainties, particularly in the rotary derivatives and ground plane effects, are carried into the simulation.

Perhaps the most serious uncertainties in recent simulator aerodynamic modeling arise from attempts to produce "modern" simulations of aircraft that have long been in service or have more recently been derived from older designs. Their aerodynamic descriptions seldom enjoy the confidence levels attributed to those of newer designs. Such difficulties have been experienced with simulations of the KC-135, P3-C, and T-37 aircraft, as well as with a number of helicopters. In general, the quality of descriptive data available for a new aircraft design tends to be proportional to the development risk; relatively little high-confidence data are produced in the development of a small training aircraft or helicopter. Obviously, the ultimate source of descriptive data, or the verification of estimated values, is flight test measurements. The growing utilization of simulators argues for obtaining data specifically for use in simulator modeling during developmental flight testing of new systems.

I.D.2: The sophistication of the newer visual and motion simulation systems has encouraged the simulation of ground-handling problems, but this in turn has challenged the simulator designer to define landing gear and braking dynamics and tire-surface friction characteristics. Experience indicates that modest levels of objective fidelity in the landing gear model bring large rewards in perceptual fidelity.

III: Modern propulsion system design processes produce elaborate computer models of the engine and its static and dynamic thrust characteristics. The simulator designer's task is to model the thrust characteristics and the engine instrument inputs with the minimum computer burden. Propulsion-systems-related uncertainties often involve the complex interactions between the propulsion system and airframe aerodynamics, particularly in high thrust-to-weight ratio supersonic aircraft designs, in V/STOL aircraft, and in helicopters.

IV: Probably because of its inherent sensitivity described earlier, no single simulation element has received more criticism than the representation of controller forces. Often these criticisms could not be answered with high confidence data, particularly in the case of systems that reflected the control-surface hinge moments. Furtunately, the advent of artificial feel systems has solved most of these difficulties, and objective fidelity is more easily assured; perceptual fidelity is another matter.

V.-VII: The modeling of aircraft systems needs few words in this discussion. There are no real barriers to objective fidelity in these simulator elements. Flight control and display systems deserve an effort to provide high objective fidelity, at least through the range of frequencies pertinent to manual control.

VIII: Modern simulator computer capabilities can readily accommodate models of a wide variety of environmental factors. The most important of these are the basic atmospheric variations that affect aircraft performance, and the wind, turbulence and shears that add important realism to the simulated flight tasks. However, the definition of suitable wind and turbulence models has been the subject of agonizing among simulation technologists because of the limited success attained to date in achieving satisfactory perceptual fidelity in simulated turbulence. (Recent discussions of this subject are presented in Refs. 36 and 37.) Attention has been given to the details of the spectral characteristics of turbulence in the assumption that therein lie the obstacles to realistic simulation; however, recent experience with large-amplitude motion simulators indicates that the primary impediment to perceptual fidelity in most simulated turbulence is the lack of translational motion cues, particularly in the lower frequency portion of the turbulence spectrum (0.5 to 2.0 rad/sec). Limited motion or even fixed-cockpit simulators present strong evidence of the attitude disturbances caused by turbulence, but the absence of translational accelerations normally associated with path disturbances due to turbulence presents a confusing contradiction and, in some cases, unrealistically difficult piloting tasks.

IX: In the past several years, research efforts have resulted in a better appreciation of the simulation difficulties that can arise from time delays and dynamic lags in the computer and cuing systems of the simulator. The general effect of such delays is to reduce the damping in the pilot-vehicle control loop and increase the pilot's workload. This incremental deficiency, when added to the effects of motion and visual cue attenuation, can be a critical factor in the perceptual fidelity of the simulated task. No simple criteria can be stated for allowable delays because their effects depend on so many other factors in the simulation. However, the subject is put in reasonable perspective with the assertion that for well-damped, fast-response (high band-pass) control modes, such delays should be held to a maximum of 50-100 milliseconds; if the damping of the simulated control mode is low, 50 milliseconds might be the target; in control modes with greater damping and lower characteristic frequency, such as those seen in large aircraft, greater tolerances to delays may be assumed, but again, if the inherent damping of the short-period control mode is low, delays of more than 150 milliseconds should be taken very seriously when perceptual fidelity is in question.

4.3.4 Objective fidelity versus perceptual fidelity

Earlier in this section, reference was made to several areas where objective fidelity in the simulator fell short of producing a satisfactory level of perceptual fidelity. The general dissatisfaction with turbulence models has been a persistent problem. A few more examples of apparent contradiction are offered here as a basis for comments on the options the simulator designer has to improve perceptual fidelity.

Longitudinal trim changes with thrust, or in ground effect — Pilot evaluation of an engineering simulation of a twin-jet transport aircraft with low-slung wing-mounted engines produced strong criticism of an apparent severe exaggeration of the pitching moments accompanying thrust changes. To provide a satisfactory level of perceptual fidelity in the simulated task (landing wave-off), it was necessary to reduce the moment arm of the engines 60 percent. Subsequent flight measurements showed the original value to be correct and the unmodified simulation to be accurate with respect to required control deflections and forces. In another instance, flight measured pitch-down characteristics of a large delta-wing bomber in ground effect were perceptually assessed as grossly excessive in the simulator compared to flight. The only explanation that can be offered is the attenuation or absence of motion cues, principally vertical acceleration, that might normally and subconsciously inspire the control inputs necessary to counter the disturbance early on.

In engineering research or development simulation, it is rarely prudent to attempt to achieve perceptual fidelity by adjustment of aircraft parameters beyond ranges of normal uncertainties. In training simulation, it might be advantageous to modify the characteristics described above by reducing the thrust and ground-effect moments; however, all effects of such changes on performance or control must be carefully examined.

Rotational damping — In an engineering simulator, in which a validated dynamic model is mechanized, there is generally the appearance of reduced rotational damping compared to the flight vehicle. From subjective comparisons of an engineering simulation and several training simulations of the same large jet transport airplane, Bray has noted that the latter were more "solid," easy to control, and perhaps more subjectively "real." The suspicion is raised that some training simulator manufacturers have learned how to, and do, adjust rotational damping terms, and perhaps other parameters, in order to produce flight-like pilot workloads while maintaining the character of the airplanes.

In summary, it can be concluded that in training simulations, adjustments of the model beyond ranges of uncertainty may be justified to improve perceptual fidelity. However, it is most desirable to understand why the adjustment is necessary and what side effects should be anticipated. Further research into the areas of pilot cuing might make this process a science instead of an empirical exercise.

4.3.5 Summary comments

The requirements for objective fidelity in the crew station and the mathematical model of the training simulator vary with training objectives; however, the general assertion can be made that the character and workload of the pilot's task in the simulator should be representative of those seen in flight.

Since simulator visual and motion cue deficiencies tend to increase workload, it is important that the "dynamic" quality of controllers and displays be maintained at a high level to avoid compounding the threats to perceptual fidelity.

In the establishment of a data base for the simulation of an aircraft system, flight tests dedicated to the objective should be conducted in augmentation of the conventional data sources inherent in the aircraft design and development process.

There is need for further information on the extent to which perceptual fidelity of simulations can be improved by deliberately departing from established objective fidelity in mathematical model dynamic response to compensate for cue deficiencies.

4.4 Conclusions and Recommendations — Technology

The discussions in this section have outlined the current status of simulation technology in the context of achieving high perceptual fidelity. Section 2, Pilot Training, strongly makes the point that high perceptual fidelity is not necessarily required to train. However, if it is determined that training is indeed limited by the available perceptual fidelity, the following are the areas that are considered to be worthy of further research and development:

Visual systems: Computer-generated visual systems offer the most cost-effective technology for improvements in visual simulation. Improved fidelity will require advances in the amount and quality of scene content. Advances in the size and shape of the field of view and the resolution of the scene display devices are the keys to exploiting improvements in scene generation capabilities.

Motion systems: The "dynamic quality" of a simulator cockpit motion system, in terms of frequency response characteristics and smoothness, is vital to its contribution to perceptual fidelity in the simulator. Practical excursion limits place severe constraints on the presentation of maneuvering-frequency motion cues for many training tasks, but experience indicates that important contributions to perceptual fidelity can be attained with modest motion amplitudes if dynamic quality is combined with optimized motion drive logic. Further definition of the principles important to optimized motion software is required. Further attention should be given to development of inside-the-cockpit "artificial" motion cuing devices to complement or substitute for cockpit motion.

Computer model of the aircraft: The degree of objective fidelity in modeling of the aircraft performance and dynamics required for various training objectives deserves further definition. The concept of deliberately departing from objective fidelity in the computer model to compensate for cuing deficiencies is worthy of further study.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Each of Sections 2, 3, and 4 provide some conclusions and recommendations from the training, physiological, and technology specialists, respectively, on the issue of simulator fidelity in relation to pilot training. In this section an attempt will be made to provide a unifying theme or overview so that those individual recommendations can be assessed in an overall context.

It is convenient to base conclusions around a reiteration of the scheme for developing simulator facilities propounded in Section 2. This process was as follows:

1. Analyze training requirements and objectives.

2. Define methods and facilities to perform the training. This is a difficult step and for discussion needs to be broken down into the following steps:

   2.1 Define objective cues that would be experienced in the aircraft while performing the task being trained.

   2.2 Define the perceptual cues experienced by the pilot in the aircraft.

   2.3 Define the perceptual cues needed to train.

   2.4 Define the hardware needed to provide the training cues.

3. Develop simulator hardware.

4. Validate the simulator. This again is a complex multi-step process which will be elaborated by the following breakdown:

   4.1 Perform objective tests against the 2.4 specifications.

   4.2 Perform training effectiveness tests. If the transfer of training is at a satisfactory level, then by definition the simulator is "validated." If the transfer of training is unsatisfactory, then steps have to be taken to determine where the deficiencies lie.

   4.3 Rework steps 1 through 4.2 until satisfactory transfer of training is achieved or alternative methods and/or facilities are resorted to.

Reviewing the work of the Working Group in the context of the steps defined above, the following conclusions and recommendations can be drawn:

Steps 1 and 2.1: More effort needs to be applied toward performing steps 1 and 2.1, but no particular research is recommended since the general techniques probably exist.

Step 2.2: There are still many aspects of this topic where technology is deficient. However, there are considerable data in the literature which need putting into more usable form for the training simulator developer. In fact, a major program has been initiated by the USAF HRL to perform such an effort; this is due to be completed in 1982.

Step 2.3: This is the area that has the biggest shortfall since there are hardly any generalizable data. An extensive research program is needed to define how cuing fidelity impacts on training effectiveness for a matrix of aircraft, tasks, pilot experience, and instruction technique. Such an effort needs to include generic training devices as well as devices matching specific aircraft. To perform such research there are several subneeds, the most important of which are models for defining facility characteristics and models for defining pilot experience and instruction technique. Such models are required so that experiments can be run in a way that will allow the data to be generalized beyond the current status of saying that motion was either on or off, and the visual system was a camera model or CGI night-only system, etc. Many more details are required to define the motion system, the visual system, the math model, and the overall system dynamics.

Step 2.4: Progress on this task really depends on progress in step 2.3; if cues to train are defined appropriately, then it should be possible to convert these cues into appropriate facility descriptions.

Step 3: Technical limitations on simulator hardware is of concern in only a few special areas, such as visual displays for helicopter NOE flying during day, visual conditions.

Step 4: Validation of the simulator is, of course, a function of the method by which the requirements were specified. Currently, validation is performed against a high-fidelity objective/perceptual model and tends to be exceedingly time consuming and expensive.

Step 4.1: If progress can be made in defining the perceptual cues needed to train and the hardware needed to provide the training cues (steps 2.3 and 2.4), then methods of performing step 4.1 should improve concomitantly.

Step 4.2: Techniques exist and have been used for performing training effectiveness studies, but there is certainly room for improved procedures. More data using the TER model are desired, and such studies should be coordinated with those performed to improve step 2.3. It is desirable to develop more comprehensive measures of simulator training effectiveness, taking into account the parameter of cost effectiveness.

It is clear that research on defining the perceptual cues needed to train (step 2.3) will be expensive and time consuming, and in fact it is unlikely that sufficient resources can be made available or even exist to do a fully comprehensive matrix of investigations. However, some tasks can be trained well in relatively inexpensive facilities, so there is no point in expending valuable resources trying to optimize these. On the other hand, some tasks need complex facilities to train well, and still other tasks cannot be trained well even with very expensive facilities. It is recommended that some effort be made toward simplifying (i.e., removing costly features from) existing facilities that do train well to determine the minimum cuing requirements for acceptable training effectiveness. Future versions of similar devices could benefit from such information. A primary effort should be devoted to defining minimum cuing requirements for evolving systems that are oriented at tasks currently not trained satisfactorily, since these are likely to specify advanced technology with associated escalating costs. This topic was not thoroughly explored by the group, but probably includes the class of simulators where both perceptual motor skills and tactical decision skills are to be trained; such devices may be epitomized by the multiple-aircraft air combat simulator. In such a case, it may be better to teach the procedures in a fixed-base cab with high equipment fidelity, the perceptual motor skills in a cheaper training aircraft with high environmental fidelity, and the tactics in a gaming simulator where the pilot sits at a simple console with joysticks for flight path controls and an analog display of the tactical situation. Such a concept could easily be extended to multiple opponents, and with application of optimal gaming techniques one or all of the other gamers could be controlled automatically to provide a more consistent training environment.

5.2 Recommendations

Recommendations for future work were presented at the end of each section: training; physiology; technology. For convenience they are collected together in this section, but the individual sections should be referred to for rationale and detailed discussion.

A major research effort should be initiated to determine minimum cuing requirements across the range of training objectives which can potentially be addressed in the simulation environment. Such an effort should not be constrained by current flight simulator practices, but should also address futuristic applications such as full-mission combat simulation, tactics development and evaluation, etc.

Procedures should be developed to bridge the gap between training objectives and specifying training device capabilities. The approach of basing the specification on the training requirement instead of the training device may have merit, and it is recommended that a thorough study of the merits and drawbacks of this alternative procedure be initiated.

Procedures for determining the training effectiveness of flight simulators should be applied and the results used for additional device procurement and design decisions. Applications should be initiated at two levels. First, attempts should be made to gather data on training effectiveness using the TER model, while ensuring sufficient quantitative definition of the facility so that the data can be generalized. A related effort should be commenced with the objective of deriving an assessment system that considers simulator/aircraft operating cost ratios and utilization rates.

Because of the wide scope and the extensive resources required for training effectiveness research efforts, it is recommended that AGARD initiate and support a collaborative multinational effort using cross-disciplinary evaluation teams similar to those engaged in this Working Group. AGARD has already initiated action along these lines in relation to visual and motion systems. It is therefore recommended that effort be concentrated on the formation of a Working Group to pursue the training effectiveness question.

Information on human sensory characteristics is not adequate to completely define the needs for simulation. Some of the material not readily available may exist in the perception literature in forms which could be made useful to the simulator community. In the visual display area, for example, the considerable literature on the relationship between visual acuity and display size, contrast, brightness, orientation, position in the visual field, velocity, and color could be brought to bear on requirements for adequate visual displays. In the vestibular field, the models for dynamic processing of combined linear and angular acceleration cues in terms of perceived orientation could be brought to bear on the design of more efficient motion platform algorithms. It is also clear that there are a number of areas covering important characteristics of the physiological sensors in which information to answer the needs of the simulator designer apparently does not currently exist. A thorough study of these gaps in the literature as well as the aforementioned collection of existing literature is of utmost importance in supporting research in simulator technology.

Research should be expanded on cuing requirements for effective visual simulation since such capabilities can greatly expand the ground training environment. There exists a need to develop models of the visual environment wherein the relevant parameters can be identified and subsequently studied to determine their impact on simulator training effectiveness.

Future research activity in the area of visual and motion cues should be directed toward applications that bear direct relationship to the cockpit simulation environment and not be limited to the traditional, simpler, laboratory experiments of the perception psychologists.

Research is required to tailor platform motion algorithms to match human dynamic processing of combined linear and angular acceleration.

Further development is required for mathematical models of spatial orientation including tactile cues.

The discussions in the technology section outlined the current status of simulation technology in the context of achieving high perceptual fidelity. High perceptual fidelity is not necessarily required to train, but if it is determined that training is indeed limited by the available perceptual fidelity, the following are the areas that are considered to be worthy of further research and development:

Visual systems: Computer-generated visual systems offer the most cost-effective technology for improvements in visual simulation, but improved fidelity will require advances in the amount and quality of scene content. More realistic size and shape of the field of view, and improved resolution of the scene display devices, are the keys to exploiting improvements in scene generation capabilities.

Motion systems: The "dynamic quality" of a simulator cockpit motion system, in terms of frequency response characteristics and smoothness, is vital to its contribution to perceptual fidelity in the simulator. Practical excursion limits place severe constraints on the presentation of maneuvering-frequency motion cues for many training tasks, but experience indicates that important contributions to perceptual fidelity can be attained with modest motion amplitudes if dynamic quality is combined with optimized motion drive logic. Further definition of the principles important to optimized motion software is required. Further attention should be given to development of inside-the-cockpit "artificial" motion cuing devices to complement or substitute for cockpit motion.

Computer model of the aircraft: The degree of objective fidelity in modeling of aircraft performance and dynamics required for various training objectives deserves further definition. The concept of deliberately departing from objective fidelity in the computer model to compensate for cuing deficiencies is worthy of further study.

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APPENDIX A

ASSESSMENT OF TRAINING EFFECTIVENESS

1. INTRODUCTION

When considering the present and future requirements for training simulators, care must be taken not to become concerned with indiscriminately extending the technology of simulation toward the achievement of the ultimate reality. Rather the aim must be to develop facilities that can train an aircrew and maintain their skills as effectively and economically as possible, while maintaining high standards of safety, efficiency, and personal confidence. Flight simulation should be employed and developed only if it can be shown to make a positive contribution to the fulfillment of the training objective. It is in this context that an examination of training effectiveness assessment procedures has to be undertaken.

Training effectiveness is concerned with determining whether a device has an effect on training performance. Effectiveness may be determined by examining if the trainee's subsequent performance on the operational tasks is improved as a result of simulator training. Alternatively, it may be assessed by ascertaining if, by the use of simulators, the required level of performance can be reached more quickly or with less resort to more costly training procedures.

There is no absence of literature on the training value of flight simulators. However, there are only a very limited number of experimental studies that have sought to determine simulator training effectiveness in objective terms.

In the main, most of the experimental evaluations of training effectiveness, which have been widely reported, have used relatively simple aircraft and trainers and have evaluated their effectiveness for the learning of elementary flying skills.

Many so-called studies of training effectiveness have relied on user opinion, detailed assessment of the physical and dynamic fidelity of the simulation in comparison with the aircraft, or the measurement of how much the device is used. None of these measures is a reliable indicant of training effectiveness.

The use of user opinion is suspect for a number of reasons. First, it assumes that the user is able to assess objectively how much he has learned from the device. Second, it assumes that the student is best able to judge what are the best learning media. Third, it fails to recognize that user opinion is based on previous knowledge and experience and that therefore wide variations in assessments of the same equipment are likely to be encountered. Fourth, judgments are sometimes based on the assessments of experienced users rather than the students. Equipment that may be damned by an instructor as being of no training value may gain this assessment because he has formed the opinion that he can gain nothing from it, and he forgets that the device is intended for the use of students and not the instructors.

Assessments of the physical and dynamic fidelity of the simulation in comparison with the aircraft give only an indication of the realism of the training equipment and not its training potential. Greater value could be put on this measure if we could be certain that high fidelity is needed in every case in order that effective training and transfer of training can take place. However, such an assumption needs to be treated with caution. First, the amount of fidelity required will vary with the nature of the task to be trained, and so training effectiveness is likely to vary from subtask to subtask rather than be represented by one unitary value. Second, accepting that some fidelity is essential, it is still only part of the total training environment. The purpose for which the device is used, the form in which the training is given, the quality of the instruction, and the attitudes of the students and instructors toward synthetic training will all influence training effectiveness. Third, high fidelity, in assessing training effectiveness, is sometimes confused with the needs of the training environment itself. This state of affairs is no more clearly apparent than in the use of large simulators in commercial aviation. The demand for high physical and dynamic fidelity is more often than not imposed by the regulatory authorities, e.g., the CAA in the United Kingdom and the FAA in the United States. These bodies set certain standards of fidelity in order that instrument rating and proficiency checks can be carried out in the simulator rather than in the aircraft. In such a role, the devices are being used as assessment tools and not training tools. Training may be possible with far less sophisticated devices. Finally, while it would appear to be the case that high fidelity generates greater user acceptance, this fact does not of itself mean that a device is a more effective training facility. For example, an aircrew may rate a device having a visual flight attachment and a motion system as being a better simulator than one which has neither of these. Whether the more sophisticated simulator is a more effective training device will depend on the tasks to be trained. It may be the case that the presence of a visual or motion system contributes nothing additional to learning achievement. Alternatively, it may be that the presence of this added facility does improve the level of training achieved, but the improvement may not be sufficiently large to warrant the increased expense and sophistication brought about by the addition of the visual and motion system.

The measurement of how much a simulator is used is not a direct or valid indication of its training effectiveness. A device's utilization time is one of the variables that enters into calculation of its cost of ownership, but the misinterpretation of these data emphasizes the distinction that has to be made between the cost of ownership and worth of ownership. The operating organization may demand figures to show that the device is being utilized as near to its design specification as possible. The demonstration of this fact does not necessarily mean that the device is being used as an effective training facility for all or part of that time. With revisions to the training syllabus, or to the methods used in training, the same level of trainee proficiency may be possible with reduced simulator operating times.

It would therefore appear that relying on user opinions, assessments of fidelity, or measures to overall utilization are not accurate and reliable guides to the effectiveness of the device as a training facility. Nevertheless, it is essential to pay attention to validating training systems. Otherwise the user may find that his students are spending more time on the equipment than is necessary, that he is

assuming that more training is being achieved than is actually the case, or, conversely, that he is achieving less training than the system is actually capable of providing.

If such states of affairs can exist, why have not more demands been made to evaluate training effectiveness along more rigorous lines? The answer to this question lies in one word, "feasibility." First, there are problems in devising appropriate methods of assessing simulator training effectiveness. Second, when adequate evaluation techniques are identified, there may be problems in actually implementing them in an actual training environment.

In order to improve the measurement of training effectiveness, it is necessary to return to the earlier definition of training effectiveness and to identify those conditions that meet the criteria for effectiveness. The first criterion is a measure based on transfer of training, i.e., examining if a trainee's subsequent performance on an operational task has improved as a result of simulator training. The second criterion is one of cost effectiveness, the contribution of the simulator being assessed by determining if by its use the required levels of performance can be reached more quickly and with less resort to more costly training procedures.

2. REVIEW OF TRAINING EFFECTIVENESS MODELS

To consider the range of training effectiveness models that can be employed, the literature on the subject has been reviewed. However, in the context for which this paper is intended, a most comprehensive examination of the problem has already been produced by Caro (Ref. 10). Therefore, rather than attempt some form of paraphrase of his study, relevant sections of the report are reproduced below.

A number of study design models can be used to determine simulator training effectiveness, some of which are more suitable to the task than others. No single design is suitable for all simulator training effectiveness studies, however. While factors such as the availability of personnel and other resources, time limitations, competing training activities, and administrative constraints sometimes necessitate use of a less than optimum study design, the investigator must guard against using a design that cannot yield information suitable to his needs.

A number of study designs that have been used in attempts to determine the effectiveness of simulator training are listed below, along with comments concerning the circumstances surrounding their use and the general nature or relevance of the information they yield. The study designs are described in terms of simple models. In general, the models are presented in order of their overall merit for use in determining simulator training effectiveness.

2.1 Transfer-of-Training Model

The transfer-of-training model generally is the study design model most appropriate to determine whether simulator training has improved subsequent operational performance. The model is based upon the basic concept underlying the use of simulators, transfer of training. Transfer of training is a phenomenon that occurs when the existence of a previously learned behavior or skill has an influence upon the acquisition, performance, or relearning of a second behavior or skill. Thus, if a behavior is learned in an aircraft simulator, and the existence of that behavior or the fact of its having been learned has an influence upon the subsequent acquisition, performance, or relearning of behavior in an aircraft, transfer is said to have occurred. The influence of simulator training can be either positive or negative. In practice, the influence may be positive with respect to some behaviors and negative or neutral with respect to others. If the sum of these influences is positive, use of the simulator can reduce dependence upon operational aircraft during training by facilitating the learning of tasks that must be performed in those aircraft.

In its simplest form, the transfer-of-training model involves two groups of trainees: an experimental group which receives simulator training prior to further training or performance testing in the aircraft, and a control group which receives all of its training in the aircraft. Alternatively, the experimental group could be participants in a newly developed simulator training program and the control group could be participants in an existing simulator program. This design permits differences in performance in the aircraft between the experimental and control groups to be attributed to the influence of training received by the experimental group. The groups must be equated, of course, in terms of relevant prior training and experience.

In all research designs involving control groups, consideration must be given to whether the control "treatment" itself might influence that group's subsequent performance in the criterion situation. The influence could be facilitative, e.g., a period of rest for the control group, while the experimental group engages in fatiguing or stressful training; or debilitating, e.g., a period of fatiguing or stressful activity such as operational missions or extended duty required only of the control group because of their availability for additional assignments. Particular care should be taken that members of neither group engage in flying or related operational activities likely to influence their performance on criterion tasks and thus invalidate experimental and control group comparisons.

2.2 Self-Control Transfer Model

Variations of the basic transfer model described above have been discussed by Gagné, Foster, and Crowley (Ref. A1), Woodworth and Schlosberg (Ref. A2), Murdock (Ref. A3), and Campbell and Stanley (Ref. A4). One variation of particular interest is useful in a situation in which a device might be used at an intermediate stage of training, i.e., when operational training is interrupted for a period of training in a simulator. In such a situation, the students in the experimental group could serve as their own controls, and performance data obtained in the operational aircraft immediately following simulator training could be compared with similar data obtained in the aircraft immediately prior to engaging in simulator training. The difference in these two sets of performance data, then, could be attributed to the intervening simulator training program. The results of such a study might be suspect, however, because of the

confounding effects of forgetting (or reminiscence), particularly if there was a significant time interval between initial and subsequent practice in the operational vehicle.

2.3 Pre-existing Control Transfer Model

There are instances in which a concurrently trained control group may not be necessary. For example, when simulator training is added to an existing training program, or when a new simulator training program replaces an old one, student performance data from the existing or older program can be compared with comparable data from the new program to determine the latter's effectiveness. For such a comparison to be valid, the pre-existing data must have been gathered under conditions which would have been applicable to a control group trained concurrently with the experimental group. A disadvantage of the pre-existing control transfer model is that differences in performance between the two groups may be the result of changes which have occurred in the population during the time between which the experimental and control students were drawn.

2.4 Uncontrolled Transfer Model

There are circumstances in which a separate control group cannot be employed, the self-control or the pre-existing control transfer models are inappropriate, and suitable control data do not exist. Such circumstances might be dictated by political, administrative, or safety considerations. For example, it might be unacceptable to "penalize" members of one group by requiring that they undergo a different and possibly inferior training program. In some instances, a control group simply may not be feasible, e.g., the effectiveness of lunar landing simulators could not be determined by employing a no-simulator training control group of astronauts.

When a control group cannot be employed and suitable control data do not exist, simulator training effectiveness can be established by determining whether students can perform a particular task in the operational vehicle, following its learning in the simulator, without an opportunity to learn that task in the operational vehicle. Data gathered under this model will be suspect since it cannot be shown conclusively that the behaviors involved can be attributed solely to simulator training. Nevertheless, such data can carry considerable weight, particularly when a task critical to flight safety is involved and a plausible case can be made that the underlying skills probably are attributable, at least in part, to the simulator training program.

2.5 Simulator-to-Simulator Transfer Model

Many studies of the influence of specific features of simulators or simulator training programs on their training effectiveness involve transfer of training from one simulator to another, rather than to operational equipment. For example, a study of the role of platform motion on pilot training effectiveness might involve training in a simulator without motion, followed by performance evaluation in the same or another simulator with motion. This design, which might be employed when no aircraft is available, is based on an assumption of equivalence, so far as criterion performance is concerned, between the second simulator and the unavailable aircraft. This is a tenuous assumption, and it is conceivable that conclusions based on transfer of training data derived through use of this model could be erroneous.

There is one situation in which the simulator-to-simulator transfer model is appropriate. That situation exists when the second simulator is the criterion vehicle. For example, the effectiveness of training in a part-task training device can be determined by measurement of performance in a full-mission simulator, if the objective of such part-task training is to reduce the use of the more complex device. In this situation, it would be presumed that performance in the simulator would involve intermediate training objectives, with the final objectives relating to subsequent performance in an operational vehicle. The situation described here is an application of one of the transfer models described earlier, with the second simulator equating to the operational vehicle itself.

2.6 Backward Transfer Model

Another simulator evaluation design, known as backward or inverse transfer of training, is based on the transfer of training concept and has been described by Adams and McAbee (Ref. A5). In a backward transfer study, an operator who already has demonstrated mastery of relevant training objectives in the operational vehicle is "transferred" to the simulator, where he is required to perform tasks corresponding to those he has mastered operationally. If he can perform such tasks to criterion levels without practice in the simulator, backward transfer is said to have occurred, and this fact is taken as evidence that transfer in the simulator-to-vehicle sequence, although of unknown quantity, will be positive.

The backward transfer design should be used with caution for at least three reasons: 1) positive results assume (possibly incorrectly) that a suitable training program exists for the simulator, 2) experienced personnel already proficient at operational tasks may have highly generalized skills not possessed by recent training program graduates and may be able to transfer to the device because of such general skills rather than skills needed to operate a particular vehicle or perform a particular mission, and 3) the simulator may be suitably designed for the evocation of a particular set of behaviors by skilled performers, but may lack the cues essential to the development of those behaviors.

While backward transfer data should not be the sole justification for adopting a particular simulator, one would be hesitant to recommend a program involving a device which could not be handled by competent pilots. Negative results could be misleading also, however. It is possible for some tasks to be performed in the aircraft by personnel who use cues not present in the simulator, and therefore they could be unable to perform such tasks in the simulator without training in it, while the same simulator may provide other cues which trainees can learn to use to perform those same tasks in the simulator for subsequent transfer to the aircraft.

2.7 Simulator Performance Improvement Model

A presumably essential feature of an effective simulator training program is improvement in the performance of trainees in the simulator as a result of training they receive in the simulator. If such improvement does not occur, there would be little expectation that subsequent operational performance would be improved as a result of simulator training. Because of this dependency relationship, improvement in performance in the simulator often is cited as evidence that simulator training is effective. This typically is done when circumstances preclude the employment of a transfer model to determine simulator training effectiveness. Examples of the application of the simulator performance improvement model are relatively common, e.g., the evaluation of spacecraft simulator training programs before launching manned spacecraft, and simulator motion system training effectiveness studies conducted in the absence of an in-flight performance evaluation condition.

Clearly, there are circumstances in which the simulator performance improvement model can provide the best available estimate of whether a simulator training program is effective. It must be noted, however, that this model yields only indirect evidence of simulator effectiveness. It can show that a necessary condition has been met, but it does not justify the conclusion that the improved performance in the simulator will result in improved operational performance. This model, thus, is most useful in a negative way: if no improvement occurs in the simulator, none should be expected operationally.

2.8 Simulator Fidelity Model

When data describing trainee performance are not readily available, other kinds of data thought to reflect simulator training effectiveness may be sought. Several models have been employed under such circumstances to generate data related to the simulator itself or to the manner of its use. One of these, the simulator fidelity model, yields data which describe the simulator in terms of its fidelity, i.e., the physical correspondence between it and the operational vehicle, equipment, or facility. Use of this model is based on the assumption that a high-fidelity simulator will yield high transfer; a low-fidelity simulator will yield less — or even negative — transfer.

The simulator fidelity model often has been used as an expedient when data reflecting trainee performance could have been obtained, although the model also has been used when no other kinds of data were available. The model has wide appeal among operational personnel who are not familiar with the complexities of transfer of training and who lack training in experimental methodology and performance measurement. It can be employed by anyone familiar with the operational vehicle, does not require test subjects and other resources, and is based on popularly accepted theoretical constructs underlying transfer of training, e.g., Osgood's (Ref. A6) transfer surface illustrating the assumed relationship between stimulus similarity, response similarity, and transfer. Systematic analytic procedures have been developed for the employment of this model that take into account fidelity of both the stimuli the simulator presents to the trainee and the responses he makes to those stimuli (Ref. A7). While such procedures increase the objectivity of the simulator fidelity data yielded by the model, they do not overcome the basic deficiency of the model itself: it yields a measure that may be unrelated to operational trainee performance.

Data describing simulator fidelity might be used as a partial basis for predicting simulator training effectiveness, but its use for determining simulator training effectiveness is inappropriate. Bryan and Regan (Ref. A8) have noted that a simulator can be a very faithful copy of operational equipment and be either effective or ineffective with respect to a particular training requirement. In fact, well-designed training equipment may deviate intentionally from fidelity in order to promote learning. In an even stronger criticism, Adams (Ref. A9) stated that equating training effectiveness with fidelity is a coverup for our ignorance about transfer and leads to the development of possibly unnecessarily costly devices. In any event, the simulator fidelity model ignores the manner in which a device is used and the objectives of device training. These two considerations underlie any determination of simulator training effectiveness.

2.9 Simulator Training Program Analysis Model

Another model, sometimes employed when trainee performance data are not readily obtainable, is the simulator training program analysis model. Use of this model involves analysis of the way the simulator is used to determine whether the training program is well designed, is directed toward the attainment of appropriate training objectives, and/or employs modern or innovative training techniques. While use of this model can pinpoint possible factors limiting the effectiveness of simulator training in a particular instance, it will not indicate whether such training is effective. Use of this model in conjunction with the previously discussed simulator fidelity model can be particularly helpful in optimizing simulator training effectiveness, but determining the extent of that effectiveness must be accomplished through use of other models.

Jeantheau (Ref. A10) suggests using these two analytic models in combination to obtain a "qualitative" assessment of simulator training effectiveness. Such an assessment does not involve measurement of any kind and is based on judgments made against a prior criteria related to training equipment and processes rather than to trainee performance. Their use in combination probably would not yield a more valid assessment of simulator training effectiveness than would either used alone.

2.10 Opinion Survey Model

There are circumstances under which one might wish to determine the effectiveness of simulator training when operational training or performance testing is not feasible, data on performance in the simulator are not available, and the simulator and its training program cannot be analyzed. For example, it is sometimes necessary to make decisions concerning the training effectiveness of a newly developed simulator (or a simulator under development) before a study based on another design model can be conducted.

Some analyses have attempted to evaluate simulators by asking operators, instructors, training specialists, and even students, their opinions concerning simulator effectiveness, i.e., the perceived training value of the device or certain of its features, or the probable impact on subsequent operational

performance of training in the simulator. Such opinion data often have little merit and even when of value may easily lead to erroneous conclusions. Rolfe has observed instances in non-Air Force training programs in which evaluations based upon operators' and instructors' opinions yielded effectiveness estimates unrelated to data subsequently obtained in transfer studies involving the simulators in question. Furthermore, the evaluations were often expressed without regard to the manner of use or the objectives of simulator training. Meister, Sullivan, Thompson, and Finley (Ref. A11) found that estimates of simulator training effectiveness based on instructors' opinions varied as a function of the different instructors expressing the opinions. The unreliability, and even invalidity, of determinations of simulator training effectiveness based on opinions of instructors and other experts probably are due in part to attitude factors such as those discussed by Mackie, Kelley, Moe, and Mecherikoff (Ref. A12), as well as to the inherent unreliability of such judgments. In the final analysis, simulator training effectiveness must be established by trainee performance, not instructor, operator, or trainee opinions about the device and its probable usefulness.

3. CHOICE OF TRAINING EFFECTIVENESS MODEL

Those measures described above that appear to offer the greatest potential benefits as assessment techniques are based on the transfer of training paradigm. They seek to derive measures of:

a. How long it takes to learn the task in the simulator

b. How effectively the task is subsequently performed in the aircraft

c. How much training normally conducted in the air is saved by the use of the simulator

These critical questions depend on having available suitable measures. In particular, measures that indicate:

a. The amount of learning achieved in the simulator

b. The amount of learning which transfers to the aircraft

c. The extent of the savings made as a result of using the simulator

These three topics present more problems than at first sight they may suggest. For, while the aims of the investigations may be clear, the methods of achieving the aims present some difficulties and ambiguities.

To assess the amount of learning achieved in the simulator, the tasks to be learned must be amenable to measurement, and criteria must be laid down to define against what standards the students' performance should be assessed to determine if and when learning has taken place. For simple maneuvers and exercises there may be little problem, but as the training becomes more complex, definition and assessment become equally difficult.

A comparable problem is that of allocating learning resources in the simulator. Assuming that a criterion for learning can be defined, how should student performance be determined? Should each student be given a fixed amount of simulator time and only those who meet the criteria performance be deemed successful? Or should students be allowed as many trials as necessary to allow them to achieve the criterion? Extreme devotion to either mode of operation is likely to be counterproductive, and from the experimental work examined it seems that the flexible application of training time to meet the criteria standards is the most frequently adopted procedure. This being so, it suggests that, for simulator training itself rather than the experimental evaluation of training effectiveness, a training policy of "training to achieve a standard" rather than "standardized training" is likely to be the more effective method of using simulation resources.

The second area in which real problems arise is that of attempting to measure the extent of the transfer of training from the simulator to the flight environment. The problem of deriving measures to determine transfer has engaged the activity of the academic learning theorist for many years. So much so that a variety of measures of transfer have been derived, none of which it would appear offers a total solution of the problem. However, the various measures would appear to be capable of being categorized into two sorts of measures. There is the "first shot" measure which attempts to determine the amount of learning transferred on initial exposure to the actual performance environment. Second, there is the "trials to criterion" measure which examines how many additional trials in the aircraft are required before the student reaches a level of performance that matches some predefined requirement. Both measures provide information about the transfer of learning. In some situations where it is essential that adequate performance takes place on initial exposure, the "first shot" criterion may have to be enforced, but nevertheless it may still be informative to follow the progress of the student during subsequent trials to determine the rate at which his learning will improve in the air. Examination of the experimental data to assess training effectiveness suggests that in trials of both measures students trained in a simulator are likely to produce high performance on "first shot" measures and continue to maintain that level of performance. However, in many of the experimental evaluations, the control group not permitted to have simulator training catches up very quickly and, after three or so sorties in the air, their performance is indistinguishable from that of the experimental group. This finding needs to be taken into account, for, while it shows the benefits of simulation training may be short-lived in terms of training effectiveness and transfer, it does nevertheless indicate that the improvement in performance takes place at the initial stages of transfer to the flight environment, where perhaps it is most valuable as it brings about the improved confidence and morale of both student and instructor. At the same time it does perhaps allow better use to be made of the initial hours spent in the air.

3.1 Worth-of-Ownership Model

This last observation leads to the third topic for discussion — that of deriving adequate and comprehensive measures that will indicate the picture of savings accruing from the use of the simulator. The

most frequently used and basic measure is a comparison of the time taken to achieve criteria. Thus, if the simulator is a device worthy of inclusion in the training program, the time required to achieve criterion performance should be achieved in either less than or the same amount of time as required in the air. However, it has been pointed out that this rather inadequate measure fails to take into account the relative operating costs of the two training devices. If it is accepted that training in the simulator can be achieved with a much lower cost than the aircraft, it follows that training in the simulator may still be effective and profitable if it takes longer than it would have done in the air. It is this extension of the consideration of transfer of training calculations to take into account operating cost factors that led Roscoe to formulate the transfer effectiveness ratio measures (Ref. A13). However, it may be the case that even Roscoe's measure does not recognize all the factors that should be included in the computation of training effectiveness. For example, the cost benefits arising from being able to provide a more precise and reliable control of training so that there is less waste of time *between* training periods and more reliable guarantees that training *will* occur at the time in which it is programmed may be a factor to be considered when assessing the worth of ownership of a flight simulator where "worth of ownership" is defined as follows:

> Worth of ownership is defined as a combination of basic factors: 1) the addition to the syllabus of tasks not previously trained on the ground (or air) prior to device utilization, 2) the ability to assess adversary tactics and own force readiness, 3) cost savings due to fuel savings, flying-hour reductions, reduced personnel/equipment requirements, etc., 4) increased flying safety, 5) training tasks that previously could only be trained during flight, 6) higher skill levels of graduates, 7) the ability to train tasks as a result of controlled environment, and 8) the ability to measure or evaluate task performance that was previously performed only during flight and therefore not observable.

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APPENDIX B

DESCRIPTION OF SOME TYPICAL TRAINING SIMULATION FACILITIES

(Data Compiled by AGARD AMP/FMP Working Group 10)

DEVICE	COMPUTER SYSTEM			MOTION SYSTEM				VISUAL SYSTEM				SPECIAL TRAINING AIDS
	TYPE	CORE MEMORY	PROGRAM LANGUAGE	TYPE	MFG	DOF	OTHER "G" DEVICES	MFG	IMAGE GENERATION	FOV	DISPLAY CHARACTERISTICS	
TA4J Flight Simulator 2F90 (9 complexes of 4 cockpits)	2-Sigma V	28K	Assembly	Cascade	Goodyear	3°	-	G.E. (2 units)	Full raster Scanned CIG/ 1000 edges Color	210°H 60°V	Mosaic of three rear proj. Flat screens, 74" from eye, floor mounted	Demonstration flights, limited performance measurement
A7E Night Carrier Landing Tnr (NCLT) 2F103 (2 units)	1-Harris 6024/1	32K	Assembly	Cascade	Vought	3°	-	Vought (2 units)	Calligraphic Night CIG	30°H 20°V	1-window on-axis pupil forming virtual display	Record/playback, auto. performance measurement
KC130F Flight Simulator 2F107 (1 unit)	2-PDP11/45	96K	Assembly	Synergistic	Singer 48"	6°	-	Redifon (1 unit)	TV Camera/ Modelboard	48°H 36°V	Off-axis reflective "Duoview"	Demo. flights auto. performance measurement
F4J Weapon System Trainer, 2F88 (3 units)	1-Singer GP4B 1-Westinghouse AN/AWG-10A	260K	Assembly	Cascade	Singer	4°	-	McDonnell Douglas (1 unit)	Calligraphic Day/Night CIG	144°H 32°V	3-window folded, on-axis virtual dislay	Limited performance measurement
F14A Flight Simulator 2F95 (4 units)	1-Sigma V	35K	Assembly	Cascade	Singer 48"	4°	-	McDonnell Douglas (4 units)	Calligraphic Day/Night CIG	46°H 32°V	1-window folded, on-axis virtual display	Limited performance measurement
SH2F Weapon System Trainer, 2F106 (2 units)	1-Harris 6024/5	64K	Assembly	Synergistic	Reflectone	6°	-	McDonnell Douglas (2 units)	Calligraphic Day/Night CIG	144°H 32°V	3-window folded, on-axis virtual display (segmented)	Demonstration flights, limited perf. measurement
P3C Flight Simulator 2F87F (5 units)	2-PDP11-45	176K	Assembly	Synergistic	Singer 48"	6°	-	Redifon (4 units) McDonnell Douglas (1 unit)	TV Camera/ Model Board Calligraphic Day/Night CIG	48°H 36°V 48°H 36°V	Off-axis reflective "Duoview" 1-window folded on-axis virtual display	Record/playback, auto. performance measurement.
S3A Weapon System Trainer, 2F92 (5 units)	6-PDP11/45 1-CSP 30 1-AN/AYK-10	262K	Assembly	Synergistic	Singer 60"	6°	-	McDonnell Douglas (5 units)	Calligraphic Day/Night CIG	144°H 32°V	3-window folded on-axis virtual display (segmented)	Record/playback, auto. perf. measurement, ltd weapons scoring
Aviation Wide Angle Visual System (AWAVS) Research Simulator T2C (1 unit)	2-SEL 32/55	96K	Fortran/ Assembly	Synergistic	Singer 48"	6°	G-Seat	Singer (1 unit) G.E. (1 unit)	TV Camera Model Board Film Scanner Full Raster scanned CIG/ 2000 edges	160°H 80°V AOI/6°-60° Zm	Spherical screen dome 10' radius, AOI projector with zoom.	Record/playback, automated performance measurement
Air Combat Maneuvering Simulator (ACMS) 2E6 (1 complex of 2 cockpits) 1	9-SEL 32/55	448K	Fortran/ Assembly	-	-	-	G-Seat G-Suit G-Dimming	McDonnell Douglas A/C 1 complex of dual domes)	TV Camera A/C models, point light background	350°H 150°V	Spherical screen dome 20' radius, 4-AOI projectors	Record/playback, automated performance measurements, weapons scoring.
F14A Weapon System Trainer, 2F112 (2 units) 1	3-SEL 32/75 1-CDC5400L 3-RDS 500	224K	Fortran/ Assembly	-	-	-	G-Seat G-Suit G-Dimming	McDonnell Douglas A/C (2 units)	TV camera A/C & Carrier Models, Pnt. Lt. Background	350°H 150°V	Spherical screen dome 20' radius, 5-AOI projectors 1-w/zoom	Record/playback, automated performance measurement, weapons scoring.
CH46 Flight Simulator 2F117 (2 units) 1	1-Harris 6024/4	64K	Assembly	Synergistic	Reflectone	6°	-	Redifon (2 units)	Full Raster scanned CIG/ 6500 edges Color	175°H 50°V + chin window	6-window folded, on-axis virtual display (segmented)	Record/playback, limited performance measurement

NOTE: 1 Systems in development to be operational in 1980-81.

U.S. NAVY FLIGHT SIMULATOR CHARACTERISTICS

DEVICE	COMPUTER SYSTEM			MOTION SYSTEM				VISUAL SYSTEM				SPECIAL TRAINING AIDS
	TYPE	CORE MEMORY	PROGRAM LANGUAGE	TYPE	MFG	DOF	OTHER "G" DEVICES	MFG	IMAGE GENERATION	FOV	DISPLAY CHARACTERISTICS	
Advanced Simulator for Pilot Training (T-37, A-10, F-16) 1	Digital SEL 3275	320K	60% Fortran 40% Assembly	60" Synergistic Six-Post Platform	Singer	6°	G-seat G-suit	General Electric	Full Raster Scanned CIG/ 2500 Edges	300°H 150°V	Mosaic of 7 inline, on-axis, "pancake" Windows	Record/Playback/ Automated Performance Measurement
Simulator for Air-to-Air Combat (SAAC) F-4	Digital Sigma V	128K	Fortran	60" Synergistic Six-Post Platform	Singer	6°	G-seat G-suit Seat Buffet	Singer Link	TV Camera/ Aircraft Model	296°H 180°V	Mosaic of 8 on-line, "Pancake" Windows	Record/Playback/ Weapon System Scoring
Large-Amplitude Multi-mode Research Simulator (LAMARS) 1	Hybrid EAI 8400 EAI 7800	128K	Fortran	30' Cantilever Beam	Northrop	5°	G-suit	Northrop	TV Camera/ Aircraft Model/ Modelboard	266°H 126°V	Spherical Screened Dome	Weapon System Scoring
Undergraduate Pilot Training Instrument Flight Simulator (UPT-IFS) T-37/T-38	Digital Datacraft 6024/4	192K	Fortran & Assembly	48" Synergistic Six-Post Platform	Singer	6°	-	Redifon McDonnell Douglas 2	TV Camera/ Model Board Night Only CIG	48°H 36°V	Single Window folded, on-axis	Record/ Playback
F-5A Flight Simulator	Digital SEL 840A 840MP TI 980	112K	Assembly	Cascade	McDonnell Douglas	3°	-	Redifon 5	TV Camera/ Modelboard	48°H 36°V	Off-Axis Reflective	Aircrew Performance Measurement 2
C-141A Flight Simulator	Digital SEL 840A	34K	Assembly	Scissors Type Platform	Singer	3°	-	Redifon 5	TV Camera/ Modelboard	48°H 36°V	Off-Axis Reflective	-
E-3A Flight Simulator 4	Digital Redifon R2000A	104K	Assembly	Synergistic Six-Post	Reflectone	6°	-	Redifon	TV Camera/ Modelboard/ Tanker Model	48°H 36°V	Off-Axis Reflective	Record/Playback/ Limited Performance Measurement
F-4E Weapons System Trainer	Digital Singer GP 4B	8K 260K Drum	Machine	- 3	-	-	G-seat 2 G-suit	McDonnell Douglas 2	Calligraphic Day/Night CIG	160°H 54°V	3-Window Folded On-Axis Virtual Display	Adaptive Flight Training/Weapons Scoring 2
A-7D Weapons System Trainer	Digital Datacraft 6024/6	64K	Assembly	Cascade	HDEC	4°	G-suit	McDonnell Douglas 2	Calligraphic Day/Night CIG	160°H 54°V	3-Window Folded On-Axis Virtual Display	Adaptive Flight Training/Weapons Scoring 2
F-111A Mission Simulator	Digital Singer GP4B	8K 260K Drum	Machine	Cascade	Singer	5°	-	Singer 2	Full Raster Scanned Color CIG/ 6000 Edges	143°H	4-Window Folded On-Axis Virtual Display	Record/ Playback 2
F-15 Operational Flight Trainer	Digital Datacraft 6024/4	72K	Fortran Assembly	60" Synergistic Six-Post	CAE Elect	6°	G-suit	-	-	-	-	Weapons System and Approach Scoring

NOTES: 1 Research Simulator
2 In Development/Installation
3 3 DOF System Deactivation with G-seat/suit Installation
4 Currently in Operational Test and Evaluation
5 Night-only CIG systems under Procurement

U.S. AIR FORCE FLIGHT SIMULATOR CHARACTERISTICS

DEVICE	COMPUTER SYSTEM			MOTION SYSTEM				VISUAL SYSTEM				SPECIAL TRAINING AIDS
	TYPE	CORE MEMORY	PROGRAM LANGUAGE	TYPE	MFG	DOF	OTHER "G" DEVICES	MFG	IMAGE GENERATION	FOV	DISPLAY CHARACTERISTICS	
UH-1 Flight Simulator 2B24 (22 complexes of 4 cockpits each)	2-Honeywell 716 1-Varian 620L	40K 24K	Assembly	Cascade	Singer	5°	-	None	-	-	-	Demonstration flights, limited performance measurement
CH-47 Flight Simulator 2B31 (1 complex of 2 cockpits)	2-PDP 11/45	72K	Assembly	Synergistic	Singer 48"	6°	Seat Shaker	Singer	TV Camera/ Model Board - - - - - - - Electronic pattern gen. for chin window	48°H 36°V	1-window folded on-axis, color virtual display 1 co-pilot repeater - - - - - - - 1-Chin window virtual display	Demonstration flights, automa..d performance measurements
AH-1 Weapon System Trainer, 2B33 (1 unit, separate pilot & gunner stations)	3-PDP 11/45	136K	Assembly	Synergistic	Singer 48"	6°	Seat Shaker	Singer	Dual TV Camera/Model Boards	48°H 36°V	1-window folded on-axis, color virtual display (both stations). Pilot has a second side window. Gunner has telescope with 2.76 or 18 FOV	Demonstration flights, automated performance measurements
Black Hawk Flight Simulator 2B38 (1 complex of 2 cockpits) [1]	6-Interdata 8/32	1408K	Fortran/ Assembly	Synergistic	Singer AST	6°	Seat Shaker	Singer	Dual TV Camera/Model Boards (1 cockpit) - - - - - - - Full Raster Scanned CIG/ 8000 Edges Color (1 cockpit)	48°H 36°V each window	2-window folded on-axis, color virtual displays 1 co-pilot repeater - - - - - - - 3-window folded on-axis, color virtual display 1 co-pilot repeater	Demonstration flights, automated performance measurements

NOTE: 1 System in development to be operational in 1980-81.

U.S. ARMY FLIGHT SIMULATOR CHARACTERISTICS

DEVICE	COMPUTER SYSTEM			MOTION SYSTEM				VISUAL SYSTEM				SPECIAL TRAINING AIDS
	TYPE	CORE MEMORY	PROGRAM LANGUAGE	TYPE	MFG	DOF	OTHER "G" DEVICES	MFG	IMAGE GENERATION	FOV	DISPLAY CHARACTERISTICS	
MRCA Weapon System Trainer (6 units in procurement)	TI 980 B	1x48K 1x36K 1x32K	Assembly	6-Post Platform	CAE	6°	G-Seat G-Suit	General Electric/ MBB	Full Raster Scanned CGI 8000 edges	108°H 38°V	3 - Window Virtual Image Displays	Record/playback automated performance measurement
Alpha-Jet Weapon System Tr[illegible]ner (3 units in [illegible]curement)	TI 980 B	2x24K	Assembly	6-Post Platform	CAE	6°	-	-	-	-	-	Record/playback automated performance measurement
F-4F Weapon System Trainer (5 units)	GP-4B	8K 245K Drum	Machine	6-Post Platform	Singer	6°	-	-	-	-	-	-
RF-4E Weapon System Trainer (2 units)	GP-4	8K 131K Drum	Machine	Cascade	Singer	3°	-	-	-	-	-	-
UH-1D Weapon System Trainer (2 units with 4 flight compartments each)	XEROX Sigma 3	2x32K	Assembly	6-Post Platform	CAE	6°	-	-	-	-	-	Record/playback automated performance measurement
CH-53 Weapon System Trainer (1 unit with 2 flight compartments)	TI 980 B	2x48K	Assembly	6-Post Platform	CAE	6°	-	-	-	-	-	Record/playback automated performance measurement
MK-41 Sea King Weapon System Trainer (1 unit)	TI 980 B	2x48K	Assembly	6-Post Platform	CAE	6°	-	-	-	-	-	Record/playback automated performance measurement
BR-1150 Weapon System Trainer (1 unit)	PB 250 Raytheon	6K	Machine	-	-	-	-	-	-	-	-	

NOTES: (1) The simulators MRCA, F-4F and RF-4E have a digital radar land mass system (DRLMS) for radar training.
The simulators MK-41 and BR-1150 have a analog/ digital radar system.

(2) The simulators MRCA and Alpha-Jet are in procurement; BR-1150 has been in use since 1966; RF-4E has been in use since 1972; F-4F has been in use since 1974; UH-1D has been in use since 1975; CH-53 has been in use since 1976; and MK-41 has been in use since June 1979.

(3) The simulators F-104G and C-160 are still in use, but are not included in the listing for they are old analog systems.

GERMAN MILITARY FORCES SIMULATOR CHARACTERISTICS

DEVICE	COMPUTER SYSTEM			MOTION SYSTEM				VISUAL SYSTEM				SPECIAL TRAINING AIDS
	TYPE	CORE MEMORY	PROGRAM LANGUAGE	TYPE	MFG	DOF	OTHER "G" DEVICES	MFG	IMAGE GENERATION	FOV	DISPLAY CHARACTERISTICS	
Singer Link 747-023 Digital Flight Simulator	XEROX SIGMA V	76K	Assembly	Synergistic	Singer Link 48 inch	6°	Buffet Device to simulate turbulence, landing, aerubuffet, ground rumble	Redifon Rigid Model Visual System	Color TV at 625 Scan rate	48°H 36°V	Flat Screen Color TV Projection, Mamoth Projectors	Wind, Wind Shear, Weight CG, Fuel Simulation. Visual Control enables day, dusk, night and various visibilities and ceilings.
Redifon DC-10-10 Digital Flight Simulator (Qty 2)	XEROX SIGMA V (2 per device)	44K per unit	Assembly	Synergistic	Redifon 48 inch	6°	"	Redifon	CCTV	48°H 36°V	Flat Screen	"
Singer Link 707-323 Digital Flight Simulator (Qty 2)	Singer Link GP-4 (7 per device)	8K per unit	Assembly	Scissors Type Platform	Singer Link 24 inch	3°	"	Redifon	CCTV	48°H 36°V	Flat Screen	"
Singer Link 707-123B Digital Flight Simulator (Qty 2)	Singer Link GP-4 (7 per device)	8K per unit	Assembly	Scissors Type Platform	Singer Link 24 inch	3°	"	Redifon	CCTV	46°H 36°V	Flat Screen	"
Singer Link 727-223 Digital Flight Simulator	Singer Link GP-4 (7 per device)	8K per unit	Assembly	Scissors Type Platform	Singer Link 24 inch	3°	"	Redifon	CCTV	48°H 36°V	Flat Screen	"
Singer Link 727-023 Digital Flight Simulator (Qty 3)	Singer Link GP-4 (7 per device)	8K per unit	Assembly	Scissors Type Platform	Singer Link 24 inch	3°	"	Redifon	CCTV	48°H 36°V	Flat Screen	"
G.P.S. LTD/American Airlines Modified Cessna Citation Digital Flight Simulator	Singer Link GP-4 (7 per device)	8K per unit	Assembly	TBD	General Precision Ltd. 24 inch	3°	"	Redifon	CCTV	46°H 36°V	Flat Screen	"

AMERICAN AIRLINES FLIGHT SIMULATORS

DEVICE	COMPUTER SYSTEM			MOTION SYSTEM				VISUAL SYSTEM				DISPLAY TRAINING AIDS
	TYPE	CORE MEMORY	PROGRAM LANGUAGE	TYPE	MFG	DOF	OTHER "G" DEVICES	MFG	IMAGE GENERATION	FOV	DISPLAY CHARACTERISTICS	
DC 8 Link (Unit #1-33)	DC Analog	None	-	TBD	Link	2°	TBD	-	-	-	-	
Link (Unit #2-33)	DC Analog	None	-	TBD	Link	2°	TBD	-	-	-	-	
Link (Unit #3-61)	GP-4	121K Drum 9K Core	Assembly	TBD	Link	3°	TBD	Link	CGI	TBD	Link NVS System [1]	
Conductron (Unit #4-52)	DDP-124	32K	Assembly	TBD	TBD	3°	TBD	Redifon	CGI	TBD	Redifon Novoview 2500 System [2]	
727 Link (Unit #2-100)	MK I	4K Core 124K Drum	Assembly	TBD	Link	3°	TBD	-	-	-	-	
Link (Unit #3-100)	MK I	4K Core 124K Drum	Assembly	TBD	Link	3°	TBD	Link	CGI	TBD	Link NVS System	
Link (Unit #4-100)	Link GP-4	9K Core 131K Drum	Assembly	TBD	Link	3°	TBD	Link	CGI	TBD	Link NVS System	
Redifon (Unit #5-200)	R-2000	48K	Assembly	TBD	TBD	3°	TBD	Redifon	CCTV	48°H 36°V	Flat Screen	
737 Conductron (Unit #2-200)	DDP-124	32K	Assembly	TBD	TBD	3°	-	-	-	-	-	
Conductron (Unit #3-200)	DDP-124	32K	Assembly	TBD	TBD	3°	TBD	Redifon	CGI	TBD	Redifon Novoview	
747 Link (Unit #1)	XEROX SIGMA V	96K	Assembly	Synergistic	Link	6°	TBD	Link	CGI	TBD	Link NVS System	
DC10 Redifon (Unit #1)	XEROX SIGMA V	56K	Assembly	Synergistic	TBD	6°	TBD	Redifon	CCTV	48°H 36°V	Flat Screen	
Redifon (Unit #2)	XEROX SIGMA V	64K	Assembly	Synergistic	TBD	6°	TBD	Redifon	CGI	TBD	Redifon Novoview 6000	

NOTES: 1 Link NVS is a night only CGI System
2 Redifon Novoview is a night only CGI System

UNITED AIRLINES FLIGHT SIMULATORS

DEVICE	COMPUTER SYSTEM: TYPE	COMPUTER SYSTEM: CORE MEMORY	COMPUTER SYSTEM: PROGRAM LANGUAGE	MOTION SYSTEM: TYPE	MOTION SYSTEM: MFG	MOTION SYSTEM: DOF	MOTION SYSTEM: OTHER "G" DEVICES	VISUAL SYSTEM: MFG	VISUAL SYSTEM: IMAGE GENERATION	VISUAL SYSTEM: FOV	VISUAL SYSTEM: DISPLAY CHARACTERISTICS	SPECIAL TRAINING AIDS
LUFTHANSA												
AIRBUS A-300	PDP 11/45	TBD	Assembly	Synergistic	Singer Link Miles 48"	6°	TBD	Redifon	(2) Model Boards (2) CGI	48°H 360°V	Redifon CCTV Monoview	
SWISSAIR												
DC 9-51	(2) SIGMA 3	TBD	Assembly	Synergistic	CAL	6°	TBD	McDonnell Electronics VITAL III [1]	CGI	TBD	TBD	
KLM												
DC-8-50	Analog	-	-	None	-	Fixed Base	TBD	-	-	-	-	
DC-8-63	SDS 930	24K	Assembly	Scissors Type Synergistic	CAE	3°	TBD	Redifon CGI	CGI	44°H 36°V	Novoview 2000 Night Only CGI	
DC-9-30	SDS 930	24K	Assembly	Scissors Type Synergistic	CAE	3°	TBD	Redifon CGI	CGI	44°H 36°V	Novoview 2000 Night Only CGI	
DC-10-30	(3) SIGMA 3	112K	Assembly	Synergistic	CAE	6°	TBD	Redifon CGI	CGI	44°H 36°V	Novoview 2000 Night Only CGI	
B-747-200	(2) SIGMA 2	112K	Assembly	Synergistic	CAE	6°	TBD	Redifon CGI	CGI	44°H 36°V	Novoview 2000 Night Only CGI	
FOKKER - VFW												
F-28	(2) TI 980B	104K	Assembly	Synergistic	CAE	6°	TBD	McDonnell Electronics VITAL III	CGI	TBD	TBD	

NOTES: 1 6-Window VITAL IV Ordered from McDonnell Electronics

EUROPEAN FLIGHT SIMULATORS (CIVIL AIRCRAFT)

DEVICE	COMPUTER SYSTEM: TYPE	COMPUTER SYSTEM: CORE MEMORY	COMPUTER SYSTEM: PROGRAM LANGUAGE	MOTION SYSTEM: TYPE	MOTION SYSTEM: MFG	MOTION SYSTEM: DOF	MOTION SYSTEM: OTHER "G" DEVICES	VISUAL SYSTEM: MFG	VISUAL SYSTEM: IMAGE GENERATION	VISUAL SYSTEM: FOV	VISUAL SYSTEM: DISPLAY CHARACTERISTICS	SPECIAL TRAINING AIDS
A 300 - B2/B4	Digital DEC PDP 11/45 PDP 11/50	90 K 86 K	Assembly	Synergistic Six-Post	Singer Link	6°		Redifon	2-Channel Raster Scanned Day/Night CGI, 400 Polygons, 2000 Lights TV Camera/Modelboard 750:1 and 2000:1 (one of these systems could be connected to each simulator)	48°H 36°V	Off-Axis Reflective 2-Front-Window Display	Record/Playback
707 - 330 C	Digital Redifon R2000	56 K	Assembly	Six-Axis Suspended	Redifon	6°		Redifon		48°H 36°V	Off-Axis Reflective 2-Front-Window Display	Record/Playback
727 - 230	Digital DEC PDP 11/45	104 K	Assembly	Synergistic Six-Post	Singer Link	6°		Redifon		48°H 36°V	Off-Axis Reflective 2-Front-Window Display	Record/Playback
737 - 130	Digital Redifon R 2000 A	64 K	Assembly	Three-Axis System	Redifon	3°		Redifon		48°H 36°V	Off-Axis Reflective 2-Front-Window Display	
747 - 130	Digital Honeywell DDP 324	56 K	Assembly	Six-Axis Suspended	Conductron	6°		Redifon		48°H 36°V	2-Window On-Axis Virtual Display (Duoview)	
727 - 230 a	Digital Systems SEL 32/55	96 K	Assembly	Synergistic Six-Post	Redifon	6°		Redifon	Raster Scan/ Calligraphic Day/Night CGI	96°H 36°V	Off-Axis Reflective 4-Window Display	
2 x 737 - 230 B	Digital Systems SEL 32/77	128 K	Assembly	Synergistic Six Post	Redifon	6°		Redifon	Raster Scan/ Calligraphic Day/Night CGI	96°H 36°V	Off-Axis Reflective 4-Window Display	
747 - 230 B	Digital Systems SEL 32/55	144 K	Assembly	Synergistic Six-Post	Redifon	6°		Redifon	Raster Scan/ Calligraphic Day/Night CGI	48°H 36°V	Off-Axis Reflective 2-Window Display	

LUFTHANSA FLIGHT SIMULATOR CHARACTERISTICS

APPENDIX C

PILOT ASSESSMENT OF TRAINING SIMULATORS

1. INTRODUCTION

The training specialist will insist that even though a high-fidelity device usually generates greater user acceptance, this fact does not in itself mean that the device is a more effective training facility.

With this qualification in mind, it was nonetheless decided to perform a survey of pilot opinions of existing training facilities. This appendix presents some of the results from that survey. The first part of the appendix presents results from an assessment of some European civil (Lufthansa, Swissair, KLM, and Fokker-VFW) and military (United Kingdom and Germany) facilities. The second part of the appendix presents results from a survey of the U.S. Airline Pilots' Association and covers civil simulators. Finally, extracts from reports by the U.S. Air Force Tactical Air Warfare Center cover the U.S. military viewpoint.

2. PILOT OPINIONS OF EUROPEAN TRAINING SIMULATORS

2.1 Introduction

In Europe, flight simulators are used on a large scale for the training of aircrew. These simulators range from old fixed-base types to very sophisticated devices with a high degree of fidelity.

In order to get some feeling for the factors influencing the effectiveness of these simulators, a limited survey was performed in the United Kingdom, Germany, Switzerland, and The Netherlands. The survey was far from comprehensive, but nevertheless some valuable information was obtained concerning the day-to-day use of training simulators.

There exists a marked difference between the civil and military application of simulators for the training of aircrew. In civil aviation, the use of simulation for the majority of the pilot's tasks is very well accepted, while in military aviation the simulator is mostly used for only certain aspects such as familiarization and procedures. This is primarily because in many military missions, particularly for fighter-type aircraft, it is much more difficult to achieve realistic mission task behavior than in civil aviation simulation. This lack of advancement of physical fidelity in military simulation results in a lot of complaints about the simulators, particularly the older units. The enhancement of the quality of simulation in civil aviation is stimulated by the government aviation authorities who have to certificate the simulators for recurrent training and proficiency checks. Such use is of great economical value to the airlines.

2.2 Civil Flight Simulators

The dramatic reduction in flying hours needed for a type qualification shows that the training value of modern civil aircraft simulators is very high. Here, the effort to reach a fair level of fidelity pays off. All the factors which make a pilot believe that the simulator is behaving like the real aircraft contribute to the transfer of training. Handling qualities are very important for learning the effect of controls, but especially the realistic coordination of control feel, motion, and visual cues are of extreme importance for the experience of fidelity. The effort spent in this area will result in good acceptance of the device.

Specific comments on motion systems indicated that the usual deficiencies (i.e., backlash, threshold, reversal bump, stepiness) were all considered intrusive. In addition, there was no difference in perceived fidelity between three- and six-degree-of-freedom systems. Complaints were also made about lack of coordination between roll and sway motions and between motion, visual, and sound cues. Indeed, the introduction of a visual system revealed inadequacies in an existing motion system.

In visual systems, the usual field of view of 48 × 36 degrees was generally considered too small. Resolution was also considered a limitation, but the changes from modelboards to CGI had improved this characteristic. It was generally considered that a dusk-dawn system was adequate and that full-daylight was unnecessary.

The success of simulation in civil aviation can for a major part be ascribed to the professional attitude of the instructor pilots who are able to create an atmosphere of realism. The application of more sophisticated simulators is not expected to result in a further substantial reduction in flying hours. The instructor pilots feel that a few hours of "confidence" training in the aircraft are necessary in order to show the pilot that he has learned the right things on the simulator. It is a widespread opinion that the proficiency checks and the recurrent training can be performed better in the simulator.

2.3 Military Flight Simulators

The data and opinions on military flight simulators were obtained from the United Kingdom and Germany. The situation in the military field is quite different from that in civil aviation. The military mission content is much more diverse, and certain elements can hardly be simulated at an acceptable level of realism. The available simulators are often obsolete and far from optimal with regard to handling qualities and even cockpit fidelity. This has caused a rather negative attitude toward the use of simulation beyond cockpit familiarization, procedures, and emergency training. Furthermore, flying a high-performance fighter aircraft is emotionally much more than a series of well-planned actions and therefore can never be substituted for by simulation. In order to accomplish an attitude change it is mandatory to expose a fighter pilot to a simulator that gives him the impression he is taken seriously.

The opinions of about a third of all RAF aircrew currently using flight simulators were collected by means of postal questionnaires and interviews, and the results of these surveys were analyzed. All the

simulators were considered to be valuable for familiarization with systems and procedures training for emergencies. With the exception of the Hawk simulator, the handling characteristics of all simulators were considered to be inadequate and required major improvements; this was of high priority, especially for the fast-jet aircraft simulators. Visual systems were regarded as useful by pilots of those multi-engined aircraft simulators which had one, but some improvements were still necessary. There was, however, no strong desire for visual systems on training or air defense simulators. The opinion of the other fast-jet operators was that major improvements in field of view and resolution were required. Such improvements together with improvements in handling characteristics were necessary before any value could be gained from the training of tactical flying and weapons delivery.

Motion systems were also considered useful by the pilots of those multi-engined aircraft simulators which had one, although improvements were desired. The requirement for motion among fast-jet crews was not so definite, although several of the systems currently employed were thought to be inadequate. Generally, there was no requirement for motion systems on training aircraft simulators, but the system provided on the Hawk simulator was considered to be both satisfactory and desirable.

Shortfalls in handling fidelity and of motion and visual systems were judged by aircrew to reduce the acceptability of present simulators. As for the civil pilots, acceptance of simulators by military aircrew is very dependent upon the status and qualifications of simulator instructors. There was a general concensus that simulator instructors should be qualified on the aircraft type and role and, if possible, be current.

2.4 Concluding Remarks

With state-of-the-art simulation techniques, it is possible to attain, especially in civil aviation, a high degree of training value.

The attitude of the instructor pilots is as important as the objective fidelity; creating a good learning set is essential for positive training results. Good objective fidelity is an asset but, due to the workload of the student pilot, not all small anomalies and imperfections are noticed by the pilot. Hence, provided he is given the essential cues, his capability to adapt makes it unnecessary to simulate with the utmost realism all perceivable details.

Simulation in military aviation (in United Kingdom, Germany, and The Netherlands) has not reached the same level of professionalism as has civil aviation.

3. PILOT OPINIONS OF U.S. TRAINING SIMULATORS

3.1 Civil Flight Simulators

To determine pilot opinion of the quality of simulators being used for commercial pilot training, information was obtained on the characteristics of transport aircraft simulators used by several U.S. airlines. Qualitative and quantitative information was obtained from representative senior airline captains on their views and ratings of the quality of simulators used in their training operations. The information from the flight captains was obtained by the Airline Pilots' Association through their training committee. Although only a limited number of flight captains supplied detailed information, the consistency of their answers is noteworthy.

No attempt was made to evaluate the effectiveness of training programs and training simulators in qualifying flight crews (captains). Experience has shown that good training programs incorporating advanced flight simulators greatly reduce the time required for crew transition to new aircraft. The relative value or quality of the elements in the training process is not discernible.

3.1.1 Pilots' Estimates of Flight Simulator Likeness to the Simulated Aircraft

Pilots were asked to rate the simulator qualities which they used during their transition training to a new aircraft. The aircraft qualities experienced during actual flight were given a baseline or benchmark for a comparison rating of 10 on each quality. If the simulator qualities were half those of the aircraft, it was rated 5 on that quality, if one-quarter, 2.5, etc. The following instructions were contained on the forms used to obtain the pilot ratings:

> "PILOT INSTRUCTIONS – Please rate the following simulator qualities experienced during your transition training to a new aircraft in relation to your subsequent flight experience in the new aircraft. The aircraft qualities experienced during actual and simulator flight conditions are given a rating of 10 on each quality as a baseline benchmark for comparison. If the simulator in your judgment has half the quality, rate it 5; if one-quarter, 2.5, etc. If similar, rate it 10, or 9 if slightly less. Use any magnitude, from zero upward, to communicate your rating of the magnitude of the simulator quality in relation to the quality you experienced when flying the new aircraft given a rating of 10 on that quality."

From the results, it was possible to convert the pilot ratings into a percentage value of the simulators' qualities or likeless to the actual aircraft experienced in flight. These results are presented below:

Simulator Rated Qualities	Percentage
Perception of External Visual Field During Taxi	39
Perception of External Visual Field During Takeoff	52
Perception of External Visual Field During Landing	50
Perception of External Visual Field During Standard Rate Turns	43
Perception of External Visual Field During ILS Approach Decision Height of Landing	51
Response of Primary Flight Instruments During ILS Approach	77
Response of Primary Flight Instruments During Cruising Flight	80
Response of Engine Instruments During Takeoff	73
Response of Engine Instruments During Cruise	79
Response of Engine Instruments During Engine Out	71
Control Forces During Loss of Engine	66
Control Forces During Loss of Two Engines, Same Side	72
Control Forces During Takeoff	69
Control Forces During Landing	53
Control Forces During Standard Rate Turns	73
Control Forces During Steep Turns	75
Control Forces During Selection of 10° Flaps	65
Control Forces During Selection of 25° Flaps	74
Control Forces During Selection of Full Flaps	71
Control Forces During Loss of Hydraulic Power	78
Perception of Motion During Taxi	46
Perception of Motion During Takeoff	70
Perception of Motion During Landing	54
Perception of Motion During Standard Rate Turns	57
Perception of Motion During Steep Turns	48
Perception of Motion During ILS Approach	57
Perception of Motion During ILS Decision Height of Landing	53

3.1.2 Pilots' Ratings of Required Aircraft Simulator Characteristics

The following 20 questions were asked to obtain an indication of how essential the pilots considered the simulator characteristics to be:

Questions	Answers
1. Was the addition of a visual scene helpful during your training?	Yes, it is somewhat essential.
2. Is there a need for daylight visual system?	Yes, but marginally helpful, not at all necessary.
3. Is a night-only visual system with dusk and dawn addition to the current system and runway markings and texture adequate for existing training purposes?	Yes, helpful but not necessary.
4. Would simulators be improved if they provide more or wider visual field and less simulated motion?	Yes, helpful but not necessary.
5. Is it possible that wider fields of external view would influence the amount of motion needed?	Yes, helpful but not necessary.
6. Was a visual system in the simulator an important factor in your learning to fly the new aircraft?	Yes, helpful but not necessary.
7. With the use of a visual system is the feel of aircraft motion necessary?	Yes, absolutely essential.
8. Do the motion cues the simulator provides differ significantly from the motion cues of the actual airplane?	Yes, and somewhat essential that they do not differ.
9. Did the simulator used for transition training have handling qualities similar to your aircraft?	Yes, and somewhat essential.
10. Is it necessary to take into account those motions brought about by the pilot in controlling the aircraft, e.g., the aircraft's rolling motion as it enters a turn and the motions induced by turbulence in flight?	Yes, helpful but not necessary, to somewhat essential.
11. Must the simulator move freely in a three-dimensional environment with six-degree-of-freedom motion?	Yes, helpful but not necessary, to somewhat essential.
12. The internal features of the simulator, its physical appearance, and the location of controls and displays and their mode of operation are precisely definable. Must there be a similar representation of the aircraft's motion, the external visual world, and the audio environment?	Yes, absolutely essential.

Questions	Answers
13. In relation to motion, do you believe that a direct simulation of the crew members by the use of dynamic seats in which the seat cushion, backs, and side panels can be driven to impose on them the sensory cues they associated with motion in flight would provide as much "realism" as six-degree-of-freedom simulators?	Yes, marginally helpful but not at all necessary.
14. Should an effort be made to create an atmosphere of realism around the simulation?	Yes, absolutely essential.
15. Did the presence of motion in the simulator have a positive effect on your performance in the aircraft?	Yes, somewhat essential.
16. Do you think your simulator was a realistic representation of the aircraft in flight?	Yes, helpful but not necessary, to somewhat essential.
17. In your judgment, if you could decide, would a motion base be used in your simulator?	Yes, somewhat essential.
18. Is there a significant difference between simulation with different motion systems (three degrees and six degrees of freedom) with respect to perceived fidelity?	Yes, marginally helpful but not essential.
19. Are you satisfied with the present degree of motion and visual fidelity of your simulator?	No, it is somewhat essential (to change).
20. Did your simulator training give you adequate preparation to transition to the new aircraft?	Yes, and somewhat essential.

3.1.3 Summary

The civil pilots indicated strong support for the use of aircraft simulators for training. They desired the cockpit of the simulators to closely resemble the aircraft. High-quality visual simulation was strongly endorsed, but the quality and amount of motion desired was less clear. All pilots did indicate that further improvements in simulators to more closely duplicate the "feel" of the aircraft are expected and required.

Simulator qualities rated lowest at matching the actual aircraft were the perception of external visual field in all of the phases specified, the perception of motion during all phases specified except take-off, and the control forces during landing. Qualities rated highest at matching the aircraft were the responses of the primary flight and engine instruments, and control forces.

The pilots' answers to questions rating the necessity of various simulator features indicated that the internal features of the simulator, its physical appearance, and the location of controls and displays must be as on the aircraft. They also considered some sort of visual system to be essential, but wider field of view and day/dawn-dusk capabilities add little. Motion was considered to be essential when a visual system was available. An atmosphere of operational realism around the simulator was considered to be absolutely essential.

3.2 Military Flight Simulators

In 1976 and 1977, the United States Air Force Tactical Air Warfare Center's Deputate for Aircrew Training Devices (USAFTAWC/TN), Eglin AFB, Florida, conducted a Simulator Comparative Evaluation (Ref. 1).

The comments which follow are taken directly from the summary section of the report.

"The purpose of this Simulator Comparative Evaluation was to subjectively evaluate and compare the capabilities of training devices in the United States Air Force, United States Navy, United States Marine Corps, Royal Air Force, industry, and the airlines.

"The consensus was that current platform and beam motion systems evaluated do not provide effective cues or enhance realism for the performance of air-to-air (A/A) or air-to-surface (A/S) tasks and enhance realism only in limited areas of transition maneuvers. The evaluation pilots felt that a sophisticated motion platform system is not required for tactical fighter training devices. Cues such as turbulence or runway feel were significant aids during instrument and transition tasks. Of the fighter-configured simulators, the simulator for air-to-air combat (SAAC), large-amplitude multimode aerospace research simulator (LAMARS), and Jaguar motion systems provided the most realistic cues for transition training; the differential maneuvering simulator (DMS) exhibited the most realistic buffet system.

"The evaluation pilots estimated that the majority of realistic motion sensations resulted from cues provided by effective visual systems. The computer-generated image (CGI) visual systems of the advanced simulator for pilot training (ASPT), TA-4J, and most airline simulators provided the most effective visual stimuli for altitude change, acceleration/deceleration, and rate and direction of turns. Simulators using dome projection systems, while providing good pitch and roll references, were less effective because of their apparent fixed position over the Earth's surface.

"Both evaluation teams agreed that an effective visual system, enhanced by optimized g-suit, g-seat, and buffet systems, would provide adequate motion cues for the performance of A/A and A/S tasks, and these are required features for future fighter simulators.

"Of the A/S systems evaluated, only CGI systems afforded the clarity and resolution necessary to recognize and identify objects at normal slant ranges.

"Color proved to be an important factor for normal object recognition and identification in A/S training devices.

"Small gaming areas increased the difficulty of performing A/S tasks by causing the pilots to expend inordinate effort to remain in the environment. Clarity, resolution, and gaming areas were generally inadequate in all camera/modelboard visual systems.

"Normal techniques and procedures could be employed only in simulators that duplicated the field of view of the aircraft.

"The evaluation pilots concluded that unrealistic performance, size, and display of target aircraft degrade air combat training and that target images must allow determination of aspect angle, range, and closure at near-realistic ranges.

"Simulator handling characteristics/flight performance that was not representative of the simulated aircraft detracted from the overall credibility of the simulator and represented a potential for negative training. Total fidelity throughout the flight envelope was not achieved by any of the devices evaluated; however, the DMS was rated as being faithful to the airplane's performance in most instances.

"Cockpit weapon panels, switches, gunsights, or heads-up displays that are not identical to those of the aircraft being simulated and the lack of realistic integration of the complete weapon system detract from the credibility of the simulator and degrade training potential. Full weapon system integration was best demonstrated by the manned air combat simulator (MACS).

"Several of the airline training devices were considered outstanding in the areas of takeoff, approach, and landing. Features that were particularly effective in airline systems included excellent resolution and clarity of the visual scene; realistic night/dusk environment, which included horizon glow, moon, stars, and effective use of light points to represent the surrounding area; and excellent airport environment, which featured correct color for flashing and steady lights, runway texturing, runway detail, and landing lights. Additionally, some of these simulators have motion platforms optimized to provide takeoff and landing roll cues, runway feel, and effective acceleration and deceleration cues."

Subsequently, in 1979, a similar study was conducted to update information contained in the earlier study. Following are the comments contained in the report of the second study (Ref. C1).

"The purpose of the follow-on simulator comparative evaluation was to evaluate those devices/developments that have occurred in the simulator field since the original simulator comparative evaluation report [Ref. C2].

"Six-degree-of-freedom motion bases provided realistic cues during takeoff, instrument flight (i.e., nontactical and mild maneuvering), and landing. A controlled scientific study is required to determine the training value of cues provided by a motion system.

"Properly integrated combinations of g-suits, g-seats, buffet systems, and the helmet loader provide useful cues during performance of tactical tasks. Current systems possess the physical characteristics necessary to provide such cues; however, a combination of all such devices must be integrated and optimized on an operational trainer.

"Computer-generated image technology has advanced to the point where adequate daylight visual scenes can be provided to train takeoff and landing tasks. In addition, the capability exists to provide limited training in some tactical tasks. Major problem areas are the poor resolution and insufficient scene content and detail.

"Altitude and ground translation cues are required to effectively train both air-to-air and air-to-surface combat tasks.

"Two very useful instructional features were observed: the ability to conduct independent training at different crew stations in multiplace simulators and the automatic performance measurement capability of the British Aircraft Corporation air combat trainer.

"Pseudo-instruments displayed on instructor operator station cathode ray tubes are superior to alphanumeric readouts of aircraft performance and may be used to replace repeater instruments on instructor consoles.

"The digital radar land mass system provides nearly perfect depictions of surface radar returns; however, care must be taken to insure that the clarity of this system does not exceed that of actual aircraft radar systems."

REFERENCES

C1	Rivers, H.A.	"Simulator Comparative Evaluation, Final Report," Tactical Air Command, USAF Tactical Air Warfare Center, Eglin AFB, Florida, 32542, November 1977.
C2	Konopatzhe, D. L. Van Arsdall, R. S.	"Follow-on Simulator Comparative Evaluation," Tactical Air Command, USAF Tactical Air Warfare Center, Eglin AFB, Florida, 32542, May 1979.

APPENDIX D

VISUAL SYSTEM TECHNOLOGY — STATUS AND PROBLEMS

1. BASIC SYSTEMS

The two most commonly used systems are based on:

a) Computer-generated imagery (CGI)

b) Camera/modelboards

Two other systems have limited application:

c) Film (photographic)

d) Shadowgraph

Presentation to the pilot for a) and b) is normally by CRT, with the information written calligraphically or scanned, and viewed on a monitor, generally via collimating optics or on a screen with a projector, generally uncollimated. Occasionally, a light valve projector with collimating optics is used.

For c) and d), the presentation is normally by direct optical projection, although, for the film system, a flying spot scanner has been used in association with normal television presentation.

A recent innovation, still under development, is the use of laser scanning. This may comprise a laser camera/modelboard/laser projector, or just the projector associated with CGI. Viewing is directly onto a screen; various collimation techniques are conceptually possible, but require considerable development.

2. FACTORS INFLUENCING THE REQUIREMENT

The eye is exceptionally perceptive and the information content of the real world is enormous. The table below lists the visual factors relevant to aircraft operation and some target values for these factors, which, while a degradation from the absolute characteristics of the real world and of human perception, if achieved would provide visual information indistinguishable in practice from reality.

Field of view	320° azimuth, +100° to -40° elevation
Brightness	400 candelas/m^2
Contrast ratio	1000:1
Resolution	1 min arc
Color	1% of true color balance
Perspective	1% of true convergence
Distortion	1%
Parallax, stereoscopy	Appropriate to real world
Depth of field	5 m to 100 km
Exit pupil	2 × 0.5 m
Dynamic response	3 min arc over complete dynamic range of aircraft
Positional accuracy	0.1 m
Operating area	300×10^6 km^2
Altitude	-100 to 50,000 ft with minimum eye height 3 ft above ground
Picture content	All details of greater than 10 mm linear dimension
Picture control	Cloud, visibility, illumination — dynamically and infinitely controllable

No current visual system can approach satisfying all of these demands; many cannot satisfy any one of the factors. The dilemma then is to choose a visual display suitable for a given training task, accepting that the choice will be task-dependent, and that for training it is not essential that the visual system present a correspondence with reality, nor even that the visual system necessarily be sufficiently representative to ensure that the pilot behaves as he would in the aircraft. The implications of these considerations are discussed elsewhere; here we consider the factors individually and outline the capabilities of the various systems and, where possible, the applications in which the factor may be of high importance. Desirable or usable levels of the factors are, of course, often conditioned by interactions between them.

3. HARDWARE CAPABILITIES

3.1 Field of View

The full field of view (320° azimuth, +100° to -40° elevation) can be generated by an array of monitors, with in-line collimation systems, based on CGI. The light transmission of polarizers and quarter-wave reflectors and transmitters is poor and results in low brightness of the picture, which consequently is in monochrome. Picture content is low unless multiple processors are used. Such systems are very expensive.

Full field of view is also obtained in shadowgraph systems. The most common application of such devices is in sky/ground projectors, where picture content is trivial and only rotational motions are represented with any fidelity. However, an alternative with six degrees of freedom has been developed using a transparent landscape model. It suffers from low brightness and poor resolution with a consequent severe limitation on the ratio maximum range: maximum altitude, about 200:1 at best. It is therefore only useful for vehicles near hover, or, alternatively, high-altitude flight. The use of a laser as the light source offers the possibility of an order-of-magnitude improvement in this ratio, due to the small size of the source, but there is a fundamental limitation on resolution due to diffraction.

The "standard" field of view available from a conventional monitor or projector presentation is in the range 40° to 50° in azimuth and 30° to 35° in elevation. Greater fields are obtained by multiplying the displays. While a 120° × 55° field has been obtained in this way, from a modelboard system with beamsplitter/mirror collimation, the complication of the optical probe, and the difficulty of merging two rows of monitors, set one above the other, leads to the more usual arrangement of just one row of monitors and a CGI data base. This gives a vertical field of only about 30° but any horizontal field depending on the number of monitors. It should be noted, however, that on side-by-side seating arrangements for the pilots, the view out of the side of the cockpit remote from the pilot is invalid. The more efficient method of collimation using beamsplitter and mirror readily allows the use of color.

The final technique is based on the area-of-interest principle in which a relatively high-definition picture of limited field of view is presented anywhere within a much larger field. Either a camera/model or CGI system may be used. The most common usage is for an opposing aircraft in air combat simulation, though ground targets, for example, may be similarly represented. The absence of a good indication of ground proximity in air combat is a substantial disadvantage, though techniques for representing ground expansion/contraction, and even translation, are being developed.

The need for a large field of view arises mainly in air combat, near hover, helicopter nap-of-the-Earth flight, navigation, and, occasionally, in ground attack on targets of opportunity. A large field of view is also required for steep turns in low-level flight, particularly where Earth-hugging, visual flight may involve rolling to the inverted, or partially inverted, condition.

3.2 Brightness

Visual displays giving levels of brightness up to about 100 candelas/m^2 are readily available. A directly viewed monitor will give this level, as do film systems. However, the presence of collimating optics makes the more usual level of the order of 15 to 20 candelas/m^2. A reduction in brightness lowers the acuity of the eye, but, with the resolution currently available in a visual system, this is irrelevant. It is a surprising result that a view of a bright sunny day presented at a brightness of about 15 candelas/m^2 is readily accepted provided the image content and contrast are adequate. At lower levels, say 10 candelas/m^2, this no longer applies. Nevertheless, in air combat simulators, the brightness of the target is typically of the order of 10 candelas/m^2, and of the sky/ground projector perhaps one-tenth of this; these appear to give a usable daylight representation of air combat.

Apart from shadowgraph displays, the visual systems reproduce the scene about 30 times/sec (European TV, 25; North American, 30). This would produce a psychologically disturbing perception of flicker were it not for the two-to-one interlace adopted, giving a field rate of 50 to 60 Hz, unless the brightness level were lowered considerably. Nevertheless, brightness levels higher than 100 candelas/m^2 will produce perceptible flicker at 50 Hz, particularly in the peripheral field.

Currently available levels of brightness in the visual scene require low levels of ambient illumination in the cockpit. Such tasks as map and chart reading then become unrepresentative compared with day-time operations. Electronic (e.g., head up) displays and the intensity of warning lights have incorrect relative brightness compared with daylight conditions.

3.3 Contrast

The ideal contrast ratio of 1000:1 cannot be generated by current systems. Large area contrast ratios of about 100:1 can be achieved by light valve projectors; CRT projectors give a value of about 10:1. Contrast is highly important in conveying information about scene content, the orientation and location of objects within the scene, the orientation of the aircraft relative to the scene, and in proper representation of atmospheric and environmental conditions. It also plays an important part in depth perception. The way in which it works, however, is not well understood.

For daylight scenes, 10 levels of contrast ratio, defined as separate shades of gray, each $\sqrt{2}$ brighter than the next lower shade, appear to be adequate. This can generally be achieved by CRT displays. However, more extreme cases occur under poor visibility conditions, where illumination ratios of lights may reach 15,000:1. Generally, that occurs at short ranges where merging of lights due to the limited resolution of simulation visual displays is not significant.

In the real world, contrast ratio decreases exponentially with distance, the phenomenon known as aerial perspective, so that objects in the visual picture become steadily lighter in tone as they recede and finally merge into the background. This indication of depth is poorly represented on camera/modelboard systems, but can be adequately represented with CGI.

Contrast appears to be of importance in all aspects of simulator operation. It is particularly important in the representation of low-visibility approach and landing, especially at night, and also in high-speed, low-level flight where range information of features is essential and, for example, the separation of hill ridges, and their relative distance, is crucial.

3.4 Resolution

A resolution of 1 min arc is well below the visual acuity of the eye under ideal viewing conditions. Static visual acuity is probably appropriate up to quite high angular velocities (20°/sec) and thereafter may fall, though there is little evidence available for the condition where the observer is moving relative to the scene, as in an aircraft, rather than the scene moving relative to the observer.

The best monitor and film displays may achieve nominal resolutions of about 3 min arc. However, modelboard/camera systems usually yield about 8 to 10 min arc, a value which is also appropriate to CGI systems after edge-smoothing has been incorporated. The resolution of shadowgraph devices may be similar, or much worse at the crucial condition of close proximity of the light source to the transparency. If a laser is used as the light source, then the effect of diffraction on resolution is important but is not well defined. Laser-scan techniques offer the potential of about 5 min arc resolution over a wide field, with some improvement over a more limited field, although spot size rapidly becomes limiting.

Under dynamic conditions, lag in the camera tube or slow refresh rates on the display may further degrade resolution, causing elongation of objects, reduction of edge contrast or of color saturation, trails, breakup of edges, or double imaging.

Lack of resolution is a major deficiency of visual systems. The observation, recognition, and acquisition of targets at representative ranges are not possible. Height judgment at low levels is severely degraded. Adjacent runway lights merge to form a bright light at long range, where they should be dim individual lights.

3.5 Color

A complete range of saturated colors cannot be achieved in currently available systems. Color saturation in itself may not be particularly important because high saturation rarely occurs in the real world.

Apart from monochromatic displays, which are now rarely used, two principal types are common: the shadow-mask monitor or light valve projector, giving a full-color spectrum, and the beam penetration tube, giving red/green, or their combination.

Color systems generally have lower resolution than monochrome, though the presence of color appears to improve the resolution, subjectively. It is an essential feature in certain tasks, e.g., landings using FLOLS, VASI, PAPI. It contributes significantly to the separation of superposed objects and to depth perception. Blue objects appear considerably brighter in the peripheral regions, which suggests that beam penetration displays may be deficient in peripheral cues if used in a wide-angle system.

In the absence of clear evidence of more subtle effects due to color, it is concluded that adequate color representation is available by appropriate choice of visual system.

3.6 Perspective and Distortion

A uniform perspective error may be said to occur as a result of an incorrect viewpoint either in the camera or computation or in the observer relative to the display. Or it might arise, for example, due to overscanning of camera or monitor. Distortion will cause perspective errors, but generally in a nonuniform manner, so that the errors vary across the viewing area. It is in this respect that distortion is important; it is unlikely to be so gross as to cause misidentification of, or failure to recognize, known objects.

While in the navigational sense the identification of known objects is the most important factor in visually determining location for a precise assessment of position (as distinct from orientation) and its change from minute to minute, perspective is of overriding importance in the judgment of position. Visual systems are capable of avoiding uniform errors in perspective; they generally contain errors due to distortion. These are due to geometrical factors (e.g., the curved faceplate of a CRT), nonlinearities in scan electronics, and optical aberrations (e.g., due to collimating optics). Lights may be of uniform size irrespective of range.

The integrity of three-dimensional scenes is destroyed by certain techniques which are used for other purposes, such as Schleimflug optics to improve the depth of field of camera/modelboard systems or vertical image compression to lower the apparent eye height. Film-based systems deliberately distort in order to manipulate the perspective changes.

Shadowgraph displays generally have an incorrect light source/viewpoint relationship.

A level of not more than 1% error is achievable near the center of displays, but probably not near the edges. However, the allowable error is not known in the training context and will be highly task-dependent. Accuracy is important where feedback of performance is an important training incentive, such as in weapon delivery.

3.7 Parallax and Stereoscopy

Direct viewing of a TV monitor requires both accommodation and convergence and creates a strong impression that the scene is not at the distance otherwise indicated by perspective or parallax. Projected, uncollimated scenes presented at a range of 2 m or more, where convergence is the predominant need, do not seem to create so strong a conflict. In reasonably collimated displays, neither feature is exhibited.

Convergence is rarely involved in an aircraft; the exceptions are close approaches to ships, oil rigs, and ground objects, generally at and near hover. However, examples where retinal disparity may be important are during landing and nap-of-the-Earth operations. It would seem that parallax is normally the overriding cue for the relative location of objects and for obstacle avoidance, but where the information content of the scene is sparse, such as over a runway or grass field and parallax cues are weak, retinal disparity may be an important aid to height judgment. Stereoscopic vision also affects the judgment of the relative size of objects at various ranges, compared with monocular vision, and the latter is further altered, depending on whether the scene is collimated. Some experimental stereoscopic displays have been produced, but none is available for normal use.

Camera/modelboard systems normally provide adequate parallax cues, which are not unduly falsified by distortions. CGI systems, with their normally much sparser scene detail, may be deficient unless the design of the model is specially devoted to the provision of parallax cues in the relevant areas of interest. Such systems normally have adequate obscuration of distant objects by nearer objects to give true parallax cuing. Film systems, on the other hand, are grossly deficient in parallax cuing; it is often wrong. Objects that obscured each other when the film was taken remained obscured, even when the intended viewpoint is changed.

Because of the importance of parallax, appendages on the aircraft which are used as sighting aids should be included in the visual simulation.

Parallax and possibly stereoscopy are particularly important in operations close to the ground, in formation flying, and in aerial refueling. Parallax may also be important in certain tactical operations, such as weapon aiming. Collimation is a desirable attribute, subjectively, of the visual scene, but its importance in training is not known.

3.8 Depth of Field

Severe limitations in depth of field occur in TV camera/modelboard systems when close to the ground. Techniques are available for varying the point of nominal sharp focus as a function of altitude to keep the important near ground in focus at the expense of the far limit. The severity of the problem is clearly a function of the minimum height and model scale. For example, at the common scale of 2000:1, adequate focus can be maintained over the range of about 100 to 1500 m with the focus set in the middle of the range. If the far limit is set at, say, 3000 m, then the near limit becomes about 250 m, well beyond the near limit during landing. Schleimflug tilt optics allow much greater depth of field for horizontal surfaces, but degrade the resolution of close vertical objects.

CGI systems have an infinite depth of field; laser camera systems, by allowing dynamic control of focus as the spot scans the modelboard, are potentially capable of providing adequate depth of field.

The poor resolution in the near field of TV camera/modelboard systems is probably a contributory factor in poor landing performance on simulators; whether it affects training effectiveness is less clear.

3.9 Exit Pupil

An uncollimated display has only one point, other factors being perfect, from which an accurate view is obtained. The picture can, however, be viewed over a large region, though distorted. With a collimated scene. good imagery can be obtained when viewed from a limited region in space. At modest departures from this region, either the imagery disappears or is unusable

Collimated projector displays have been produced with an exit pupil approaching the 2 × 0.5 m quoted previously. This is of particular value in transport aircraft, allowing pilots one and two a good view and an adequate view for a third pilot. A similar solution for both observers in a tandem arrangement has not been produced. Collimated monitor displays generally have a much smaller exit pupil, in the order of a few centimeters. Consequently, displays consisting of several monitors to provide a large field of view either give an adequate view to only one observer or split the total field of view so that only half is appropriate to each of two observers.

A large exit pupil is useful in allowing a comfortable range of head movements while retaining an adequate visual scene. For most training needs, this is unlikely to be of great importance. However, where large field of view is required to both sides on a side-by-side configuration, or where the instructor and pupil both require a good view (in ab initio training, for example), a large exit pupil is desirable.

3.10 Dynamic Response and Positional Accuracy

Aircraft can generate rotational rates up to about 6 rad/sec, accelerations up to 6 rad/sec^2, and translational rates of, say, M = 2, and accelerations of, say, 8 g. Conventional probes of camera/modelboard systems cannot achieve this performance, though specially modified ones have approached it; there is no doubt that a probe could be produced with adequate response. The achievement of the translation performance is largely dependent on model scale, but should be comfortably met at a scale of 2000:1. A positional accuracy of 0.1 m cannot be achieved at this scale, with a reasonable maneuvering area, but can be approximated by techniques involving the feedback of the visual scene position into the computation of the aircraft model. The accuracy is, of course, nominal and ignores errors due to distortion which may displace objects, particularly in the far ground, by very large absolute distances. From the point of view of piloting, it is the angular error that matters in this case, but, from the point of view, for example, of miss distance in weapon attack, absolute distance is important.

In principle, CGI systems have no difficulty in achieving the response nor in meeting the static accuracy, which is only a function of the resolution of the least significant bit as a proportion of the total range.

Control and disturbance inputs may produce appreciable power in the response at frequencies up to several Hertz. However, for training purposes, adequate visual information at frequencies up to about 1 Hz should prove acceptable even for the most lively aircraft. Camera/model systems can keep phase errors below about 20° at this frequency, a value which cannot normally be matched by CGI systems. However, provided transport delay does not exceed 100 ms, no problems should be caused by lag in the visual display, unless particularly poor aircraft dynamics are to be considered.

Good dynamic response is important, particularly where aircraft handling qualities are an essential element of the training. Ab initio training, where the pilot is learning correct interpretation of visual information and assessing the response to a variety of control inputs, is the obvious case. The importance of visual system accuracy in weapon delivery has been indicated above.

3.11 Operating Volume

The operating area of 300 × 10^6 km^2 and altitude range from -100 to 50,000 ft, combined with a minimum eye height of 3 ft, can be met simultaneously only by CGI systems. At best, in modelboard systems, the minimum eye height (in feet) is about 0.01 of the scale ratio, with a corresponding maximum altitude (in feet) of one to two times the scale ratio. Shadowgraph displays with models have a value for the factors nearer 0.05 and 0.5. The operating area of modelboard systems is constrained by building size, lighting requirements for TV camera systems, positional accuracy for a given scale, and, in practice, is normally about (scale ratio/100)^2 (in square kilometers). Thus, a scale between 1000:1 and 2000:1, giving a minimum eye height of 10 to 20 ft and an operating area of 100 to 400 km^2, is suitable for takeoff, circuit approach, and landing, depending on the size of the aircraft; whereas 10,000:1 would be acceptable for low-level operations (e.g., terrain following) over a reasonable range (say, 100 to 150 km). Scales as small as 40,000:1 have been produced to allow a limited cross-country capability. Large scales (cf. 1000:1) have also been produced for V/STOL and helicopter operations.

A reasonable operating volume is important mostly in military operations. However, this is associated with a need for considerable picture detail — more than is at present available from CGI. While air combat, formation flying, and in-flight refueling also consume large operating volumes in reality, in simulation the current visual systems for these activities are not Earth-related and consequently are unaffected by the operating volume. Inability to acquire the "other" aircraft at a distance is more restricted by resolution than maximum range available from the visual system.

3.12 Picture Content

Everybody knows what picture content is, but nobody knows how to define it. The important parameter is the amount of information conveyed by the scene rather than the amount of detail. The maximum detail would arise by ensuring that in the display each pixel was different in color or tone from all adjacent pixels; such a display would not necessarily contain much information.

CGI systems conventionally define the complexity of the scene by numbers of edges or polygons and light points available. Complexity in this sense is increasing steadily from about 10,000 edges toward 30,000 to 50,000 edges/channel. Several channels can be employed, at a price. Texture is being implemented on CGI displays in an attempt to compensate for the gross deficiency of edges compared with reality. Complexity of modelboard systems is largely dependent on the skill and enthusiasm of the modeler, but edges well in excess of 500,000 can readily be produced and 1 million is not too difficult. The heaviest demand on edges arises from cities and landscape (trees, hedges, etc.), although the latter (and possibly elements of the former) may be represented by generalized, but appropriate, texture.

Subjective judgments by qualified observers of the relative complexity of scenes are remarkably consistent. Since measurements cannot be made with the same reliability, it is not possible to identify specifically the information content, in terms of its "usefulness," of a given display. Spurious content, e.g., dots of a shadowmask tube or raster lines, may also modify the information content by, for example, "breaking up" an object and thereby camouflaging it. The manner in which information in the real world is selected and manipulated is not known, but there is evidence that the strategy adopted differs markedly between observers. For a given task, the content of a sparse scene may therefore be to the liking of some observers and not to others.

Where recognition and identification of objects in a realistic background is the important element in the task, it would appear that only modelboard systems currently offer an approximation to sufficient picture content. Similarly, maintaining adequate ground clearance in low-level/high-speed flight (contour flying) requires a rich scene only available from modelboards, although this may be counterbalanced by the limited operating area. On the other hand, where the actual process of target attack is the main task, then CGI offers a better alternative, giving accurate feedback of performance, allowing the introduction of moving targets, the representation of own weapon effects, and enemy response. The insertion of CGI elements into a modelboard-based system offers a combination to cover all aspects. However, synchronization to take account of the phase lag in the camera drive and transport delay in the CGI is difficult; it may be most readily accomplished with a laser camera system, where the laser can provide the synchronization pulse via a detector in the modelboard.

3.13 Picture Control

The features of interest are visibility (cloud, fog), precipitation (rain, snow), and illumination (day, dusk, night). Modelboard systems provide control of cloud base by "whiting out" the picture, either electronically or by mechanically interrupting the optical path of the camera. Patchy cloud, or operation above cloud, is not normally provided, although some developments in both areas have been made. Entering and leaving cloud is usually unrealistically rapid, although with electronically controlled interruptions this can be fully under control. Low visibility is achieved in a similar manner by partial obscuration of the scene, but since it is achieved in a two-dimensional manner, operating on the video link, the tops of vertical objects are obscured prematurely. A system based on a laser camera can, however, potentially

overcome this effect by dynamic control of the visibility as a function of the range of the object in a similar manner to the dynamic control of focus.

CGI systems do not suffer these deficiencies. Control of the "visibility" of objects is direct. They are also more readily adaptable to dynamic control of visibility (e.g., patchy fog), although patchy cloud can only be achieved by consuming some of the available stock of edges.

Scene illumination can readily be varied by changing the model lighting of modelboards, but night scenes cannot compare with the versatility of CGI systems and cannot be adequately represented at the smaller scales due to the difficulty of feeding discrete lights of miniscule dimensions into the ground plane. For the same reasons, dusk scenes are generally sparse in lighting by comparison with comparable CGI systems, but are generally richer in ground features. The noise in the visual scene of camera-based systems is generally excessive at low illumination.

Precipitation has not been simulated in the visual systems currently available. Indeed, the effect of atmospheric moisture in fog simulation is poorly represented in the creation, for example, of halos on lights and back reflection of landing lights. Representations of these features is most important in training for low visibility (Cat I, Cat II, Cat III) landings and for other adverse weather conditions, e.g., windshear. Nap-of-the-Earth and contour flying is another important activity where picture content control may be needed.

4. OTHER APPLICATIONS AND DEVELOPMENTS

4.1 Night Operations

A variety of aids to operating at night are used in aircraft, for example, night vision goggles, low light television (LLTV), and forward-looking infrared (FLIR). The application may be to head-up or head-down observation, but, in either case, the simulator visual display is a candidate for the provision of the images.

There would appear to be little difficulty in generating LLTV using either a modelboard system or CGI. There is a need for a zoom facility to vary image magnification, easily accomplished by programs in CGI, and such an addition has been incorporated in a camera probe. Where the scene is presented on a head-up display (HUD) and it is wished to retain the true outside image, two channels will be required; keeping them in synchronization will require highest quality servos on a modelboard system.

Much more difficult is FLIR. Since the image is IR and not visible radiation, the information is not contained intrinsically within a modelboard. A special modelboard can be constructed, but the scene is different by day and by night and varies during the transition from one to the other. The lower picture content would favor CGI, but the scene needs to be blurred in a tonal sense. Tonal transformation is time consuming. Variation from day to night, given the flexibility of the CGI data base, should be possible.

Night vision would appear to need the introduction of filters between the display and the pilot's eyes to maintain adequate contrast in the scene. This should be possible and has been achieved for a projected scene.

All of the above applications require only a monochrome display and, for the modelboard system, considerably reduced lighting.

4.2 Area of Interest

Only the fovea is capable of the highest resolution. Head- and eye-following devices are available so that it is conceptually possible to design a visual system with the highest resolution and picture content in a limited area, say, 15° × 15°, centered on the sight line, with lower resolution outside this area. Such a system might have specific value when used in conjunction with helmet-mounted sights. Alternatively, it would have a place in improving the picture content of CGI displays in the important viewing area. There is, however, an overhead in computing the current viewpoint, and reduction in transport lag is at a premium so that, on changing his point of regard, the observer does not see the sparse area before the detail arrives.

Considerable development would be required to perfect such a system.

4.3 Head-mounted Visual Scene

Development of the helmet-mounted sight naturally leads to the proposition for a head-mounted visual scene. This offers a detailed scene, possibly of a limited instantaneous field of view, but available over a large total field without the need for multiple monitors or slewing projectors. In this case, the camera of modelboard systems is slaved to the head position, and for CGI the same arguments apply as in Section 4.2 above. There is, however, an additional burden in both cases — the observer must not be able to see the outside scene where it should be obscured by the aircraft structure, a restriction not easily accommodated.

4.4 Hologram

In principle, one holographic plate can contain a large amount of information from multiple viewpoints. In practice, a means of extracting the information in a useful form for flight simulation has not yet been devised. When directly viewed the information is three dimensional. A limited application is the viewing of portions of a hologram, illuminated by laser and directed by mirror reflectors, with the projected image transmitted to a monitor using a TV camera fitted with a zoom lens. This avoids the modelboard of camera systems, but otherwise is similar, but with a very restricted operating area. One of the main difficulties of holographic techniques is the control of the selected viewpoints, rather akin to selection of appropriate frames from multiple film strips.

5. MISCELLANEOUS DEFICIENCIES

5.1 Camera/Modelboard

The picture is produced by raster scan, which takes time to generate a complete picture. Since the visual scene is normally dynamic, the viewpoint moves during the creation of the picture. There are a number of consequential anomalies.

For example, during rapid yawing, vertical objects will be sheared, i.e., while horizontal edges will remain horizontal, vertical edges will appear tilted. Further, due to the two-to-one interlace, the vertical edges will be ill-defined; a band of lower contrast, or changed color, occurs at each edge. Pitching motion, giving a vertical movement of an object over the viewed scene, causes a similar effect on horizontal edges and, in addition, causes object compression or expansion, depending on the direction of movement relative to the scan sequence. Due to lag in the camera tube, and phosphor persistence, there is a reduction in resolution during image translation, and smear of images, which may cause light trails, particularly in night scenes, or a color trail where phosphors with different persistence are used.

It is not known whether the distortion of images or their edge blurring affects the pilot behavior; subjectively, the effects are scarcely noticeable. Light trails converge on the instantaneous aiming point and thus give useful information not available in the real world.

5.2 CGI

CGI systems take a snapshot of a complete field or a complete frame and consequently do not suffer tilting of objects; if the update rate is every frame, neither do they suffer edge blurring. If update is at field rate, then, because a complete picture contains two fields which in the dynamic situation are from different viewpoints, vertical edges will appear jagged during a yawing maneuver and horizontal edges will be extended vertically in a pitching maneuver. Small objects which are translating vertically across the screen may appear as two elements instead of one (e.g., runway lights during takeoff). Objects may also disappear if they are very small, e.g., a dividing hedge between fields, if they occupy only one raster line which is being computed in the TV field not being displayed. The doubling effect also occurs on beam penetration displays with a low refresh rate.

Due to the discrete nature of the computer generation, and the display on a raster format, a number of visual anomalies occur.

These take the form of tearing of features, differential apparent movement, or jumping of details. For example, when parallel lines (oriented near vertical on the display) occupy only a few raster lines, then, when turning toward these lines, the nearer line appears to be moving toward the observer, the farther line away from him. Or if a feature in the distance occupies only a few raster lines, it may disappear if descending below a given angle relative to the feature and reappear on increasing the angle — a very good spurious glide-slope indicator.

5.3 Displays

If a pilot scans across a stationary display, then head and eye movements may interact with the refresh of the display, giving flicker in the display. Similarly, when the scene is moving, such a scan can suppress the movement of objects in the display, reinstating them with an apparent jump when the saccadic movement of the eye ceases.

Where a gap exists between displays in a multiple display system, illusions as to the continuity of features across the display gap may occur.

A number of deficiencies are associated with collimating systems. In general, all parts of the scene are not at the same range; sometimes the image is on the observer's side of the optics, implying converging rays to the eyes (or negative squint), and in others the image is not at the same elevation relative to the two eyes (dipvergence). All these features lead to eyestrain in the observer.

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Technology is allowing the simulation of increasingly complex flight situations with more and more fidelity. High fidelity generally implies high cost, but high fidelity is not always necessary to obtain satisfactory training. This report addresses the subject of fidelity of simulation for pilot training and provides background to specialists in the multiple disciplines involved. Topics presented in detail are: the training psychologist's views on fidelity of simulation required to train, and methods of assessing this fidelity; the physiologist's survey of pilot cueing mechanisms, in particular those provided by motion or visually induced motion sensations; and the simulator technologist's assessment of existing motion, visual and aircraft mathematical model technology and the characteristics which could be expected to provide high perceptual fidelity.

In each of these disciplines deficiencies were identified in the current ability to relate simulator fidelity to the needs for pilot training and recommendations are made for structuring future research efforts.

This report was prepared by a Working Group co-sponsored by the Aerospace Medical Panel and the Flight Mechanics Panel of AGARD.

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